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Review

PCM-mortar based construction materials for energy efficient buildings: A review on research trends

V. Venkateswara Rao[a], R. Parameshwaran[a,*], V. Vinayaka Ram[b]

[a] Department of Mechanical Engineering, Birla Institute of Technology and Science-Pilani, Hyderabad Campus, Hyderabad 500 078, India
[b] Department of Civil Engineering, Birla Institute of Technology and Science-Pilani, Hyderabad Campus, Hyderabad 500 078, India

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ABSTRACT

The increasing concerns about climate change and environmental emissions have led to conservation of energy in buildings through the development of several energy-efficient technologies. Though, the energy requirements in buildings are being continuously addressed, factually, the buildings across the world consume almost one-third to one-quarter of the total energy being produced. From this perspective, the development and incorporation of the energy efficient materials and technologies in buildings in order to fulfill the cooling energy requirements have been gaining impetus, in recent years. The building envelopes which may seem to be consuming more energy can be modified by tailoring the construction materials, such as mortar, with heat storage materials for regulating the indoor temperature and achieving enhanced energy efficiency as well. The phase change material (PCM)-based thermal energy storage (TES) is one among the efficient technologies available, which seems viable to cater to the end-use energy demand through energy redistribution. This is possible because of the storage and retrieval of the latent heat during the phase change processes at nearly isothermal conditions. The prime intention of this article is to review the literature involving synergy of PCM and mortar for achieving energy efficiency in buildings. The review includes details regarding different PCM-mortar combinations along with details pertaining to, but not limited to, thermal and mechanical properties of the PCM-mortar. The period, post 2010, has been observed to be very productive with many researchers actively carrying out the investigations related to this very important area of research and hence the period between 2010 and 2017 has been specifically chosen for this review article. The selection and application of a variety of the PCM-mortar combinations in buildings have been extensively reviewed from the perspectives of porosity, supporting materials, thermal and structural properties. Furthermore, the advantages and limitations associated with each kind of mortar for its utility as PCM carrier have also been summarized.

Contents

* Corresponding author.
E-mail addresses: venkat4523@gmail.com (V.V. Rao), parameshwaranr@hyderabad.bits-pilani.ac.in, parameshviews@gmail.com (R. Parameshwaran), vinayak@hyderabad.bits-pilani.ac.in, vinayaka.vr@gmail.com (V.V. Ram).

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1. Introduction

Energy is the prime mover for all day to day human activities and its conservation through efficient utilization is crucial for economy of any country to sustain in the long run. Moreover, environmental pollution due to excessive usage of fossil fuels is of primary concern for all the countries of the world because fossil fuels are limited and are depleting at a faster pace. It has been observed that almost all the countries of the World are consciously trying to cut the usage of fossil fuels through technologies involving alternate energy resources. Incentive driven economic policies for the extensive utilization of alternate or renewable energy options is picking pace in majority of the countries of the World.

The countries grouped under the banner of organization for economic cooperation and development (OECD) have made a conscious effort of reducing the gap between power demand and supply by switching over to renewable energy based technologies. It may be noted that the global energy demand is increasing by 1.4% every year and the buildings alone, residential and commercial together, contribute 40% of global energy consumption [1].

Solar energy has been the primary energy source available to the entire globe around the year and energy received from this source by earth is estimated as 10,000 times that of global energy demand [2]. This energy resource can be used through a thermal storage medium like phase change material and decrease active energy consumption through heating, ventilation and air conditioning (HVAC) systems in buildings. This could be possible through incorporation of PCM in floors, walls and ceilings of buildings and satisfy all dimensions of sustainable development from social, economical and environmental points of view. PCM changes its phase with ambient temperature and can absorb and release heat during phase change and when incorporated into mortar, will serve as passive thermal regulator of indoor temperature. If PCM has to function as thermal regulator, its phase transition temperature should lie in the vicinity of ambient temperature. Though PCMs could be included in floors, ceilings and as storage medium for heat pumps and solar collectors, its application in walls of buildings is most sought after [2].

It has been reported that PCMs possess high energy storage density and temperature variation attenuating capacity [3]. Despite the fact that the construction material behavior becomes very complex with the inclusion of PCM, it has been verified on many occasions that the resulting composite is still acceptable as a construction material in general and light weight material in particular. Another distinctive advantage of using PCM is that it is typically a latent heat storage medium, occupying less volume when compared to sensible thermal storage media [3].

Leakage and compatibility with the mortar have been observed to be the major areas of concern as far as PCM use in mortars is concerned. However, these problems can be addressed by proper method of PCM incorporation in to mortar. The usual methods of incorporation of PCM in to the mortar, adopted by researchers, are direct mixing method, capsule bending method and immersion method [4].

The use of PCM is quite common in gypsum wall panel boards, concrete and mortar, as reported in the literature. Incorporation of PCM in prefabricated gypsum wall panels is a controlled process and hence they pose relatively less challenges when compared with mortars and concretes. In concretes and mortars, which are primarily in-situ products, careful process has to be devised and followed while adding PCMs in to the respective matrices.

While mortars constitute cement (or cementitious constituents), fine aggregates (river sand or crusher rock dust), viscosity modifying admixtures or super plasticizers along with water; concretes will have coarse aggregate chips in addition to all the ingredients which are available in a mortar. A separate research track has been followed with PCM enhanced concretes as concrete possesses higher thermal inertia when compared with mortars.

Also Concrete is considered a structural material while mortar is literally a functional material without much demand from the mechanical strength point of view. Most of the works have reported paraffin wax as the PCM being tried with concrete [5]. Few studies reported that there is a compromise from strength and fire resistance points of views when concrete is made with PCMs [6]. However, in this article, a detailed review of literature during the period 2010–2017 was taken up for the specific case of PCM enhanced mortars only.

- In addition to the current first section, complete literature review is presented in 4 more sections.
- Second section discusses about building energy consumption status and short description on latent energy storage system.
- Third section concentrated on different PCM and their thermal properties followed by different mortar-PCM combinations and thermal storage properties of PCM-mortar.
- The fourth section briefly describes numerical as well as experimental studies with the relevant properties which a decision maker may be interested in.
- The fifth section summarizes the review work reported in this paper on the PCM-mortar combinations for building applications.

Section details of the literature review are summarized and presented in Fig. 1 for quick reference. The last section concludes with key technical interpretations and recommendations. An overview of the contents of this paper is presented through Fig. 1. Fig. 2 depicts the rising interest in this research area, thus indicating that the world started focusing on passive temperature regulation strategies for indoor thermal comfort, achieved economically with reduced power consumption. Compatibility of mortars with different PCMs has also been thoroughly reviewed in this article to make it useful for the research community at large.

2. Energy consumption in buildings

2.1. Global energy scenario

Efficient utilization of energy has always been a matter of concern for the humankind. Buildings, belonging to different functional

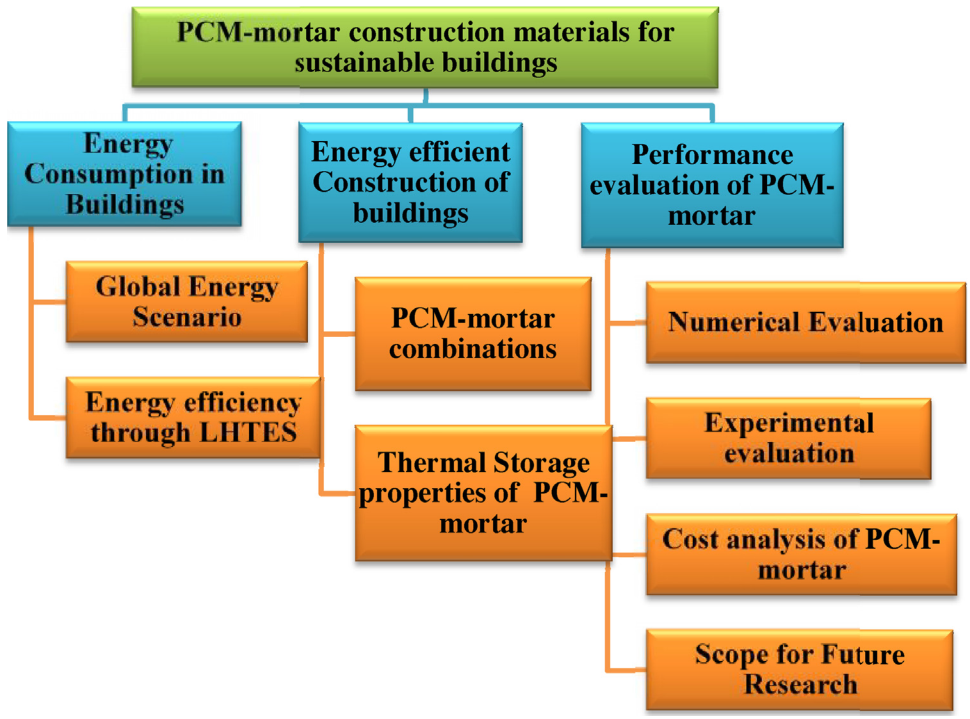

Fig. 1. Organization of review paper.

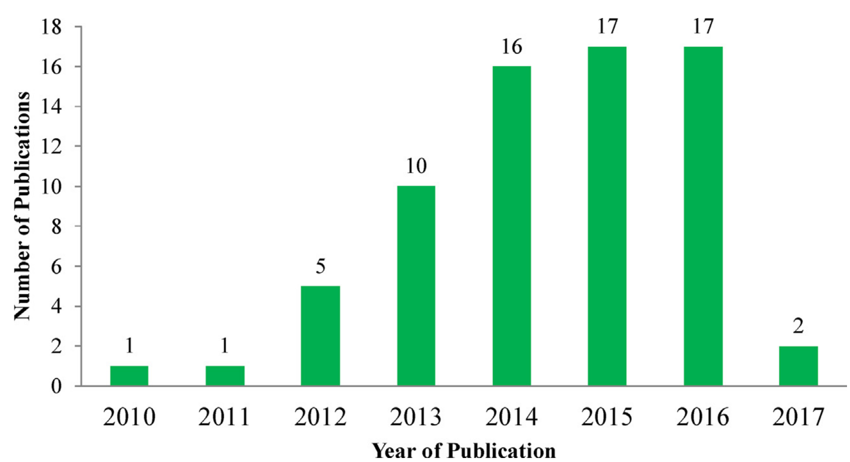

Fig. 2. Number of articles pertaining to PCM-mortar considered for review-year wise (2010–2017).

classes put together, are known to be the major energy consuming entities. To have a fair idea about the global energy consumption scenario in this sector, this section is dedicated to energy consumption in buildings in general, wherein the energy consumption scenario in buildings is highlighted, so as to enable the reader to realize the importance of global energy management scenario.

To depict the energy consumption in buildings across the globe, three of the biggest economies in the world, namely U.S.A, European Union, China, are considered for the current discussion. These countries, together, have reported that the energy consumption has got increased by 85% and the corresponding CO_2 emissions have gone up by 75% during the period from 1980 to 2012. It has also been reported that China's consumption of energy has surpassed that of U.S.A. since 2010due to enormous growth of China's economy during the recent past. Further, in China, Energy consumption has gone up by 40% during 1990–2009 [7].

If specific energy consumption is considered, it is found that space heating and water heating requirements are higher than others in all the three economies considered. Energy consumption for cooling of space stands last in the energy demand hierarchy. There exists diversity in specific energy requirement for all the three economies considered. In U.S.A., the demand for heating space accounts for about 37% of entire residential energy demand. In China, the energy demand for heating of space and water is about 71% and 68% respectively. In European union, energy consumption for space heating is highest accounting for about 66% of entire energy demand [7]. Fig. 3 depicts the heating and cooling requirements, highlighting both residential and commercial sectors.

It is interesting to note from Fig. 3 that the energy requirements for the residential buildings are far more than that required for commercial buildings. However, the energy demand for commercial operations is on steady rise as can be observed from Fig. 3.

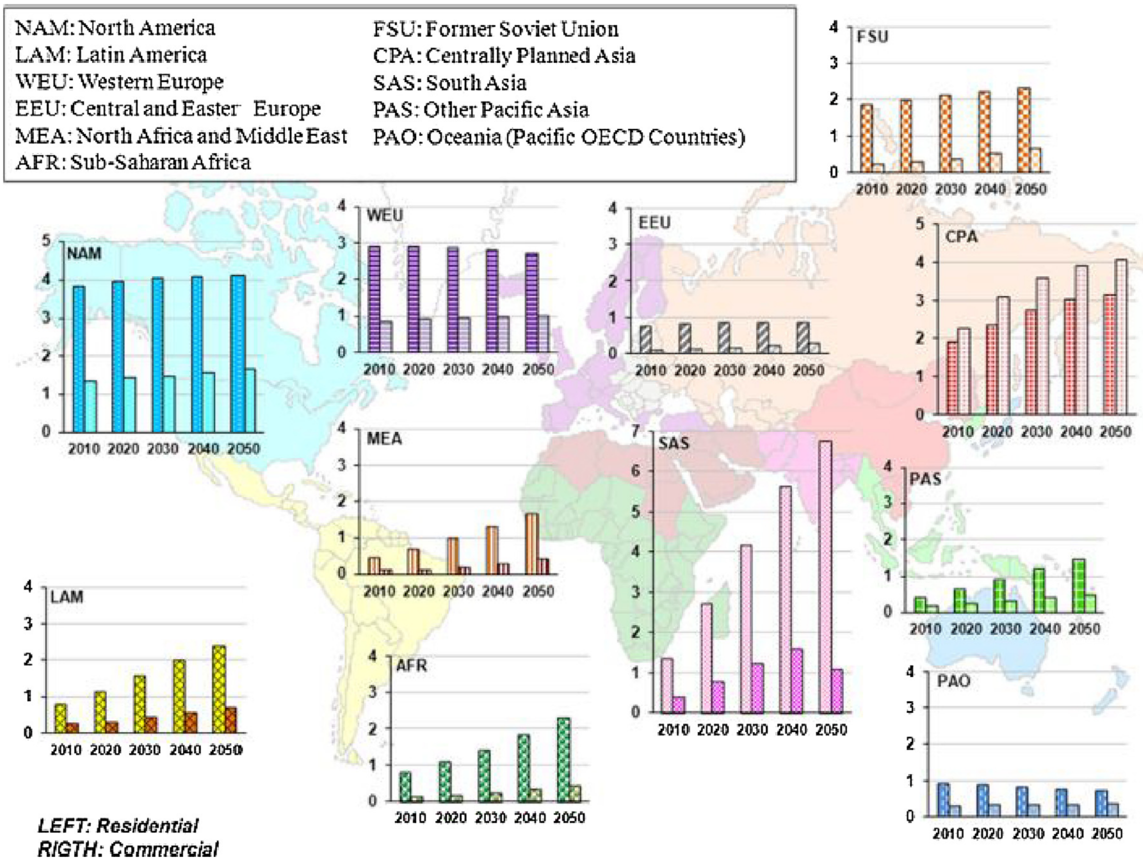

Fig. 3. Heating and cooling requirements all over the world (residential and commercial) [8].

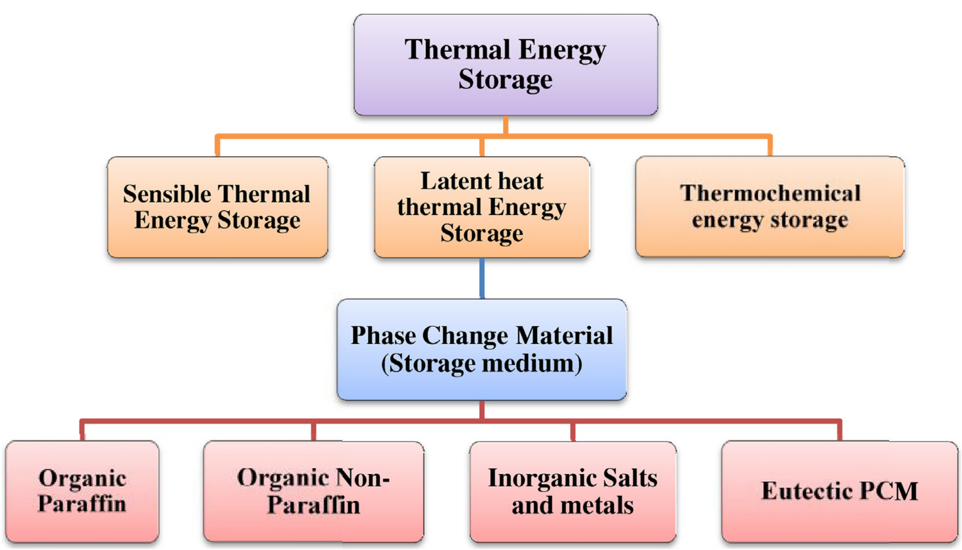

Fig. 4. Classification of TES (thermal energy storage) technologies.

2.2. Energy efficiency through latent thermal energy storage

The primary aim of this paper is to provide an overview of the incorporation of phase change materials, with desirable properties, into mortar, used for wall plastering applications, to improve the energy efficiency of buildings subsequently improving the indoor thermal comfort.

Thermal energy storage technologies can be broadly classified as sensible energy storage, latent heat thermal energy storage and thermochemical energy storage. Fig. 4 presents the hierarchical classification of thermal energy storage technologies and in particular about PCM as storage medium for latent thermal energy storage.

Phase change material falls under the category of latent heat thermal energy storage technology. Sensible energy storage involves storage of thermal energy by increasing the temperature of the substance or material. Latent heat thermal storage involves

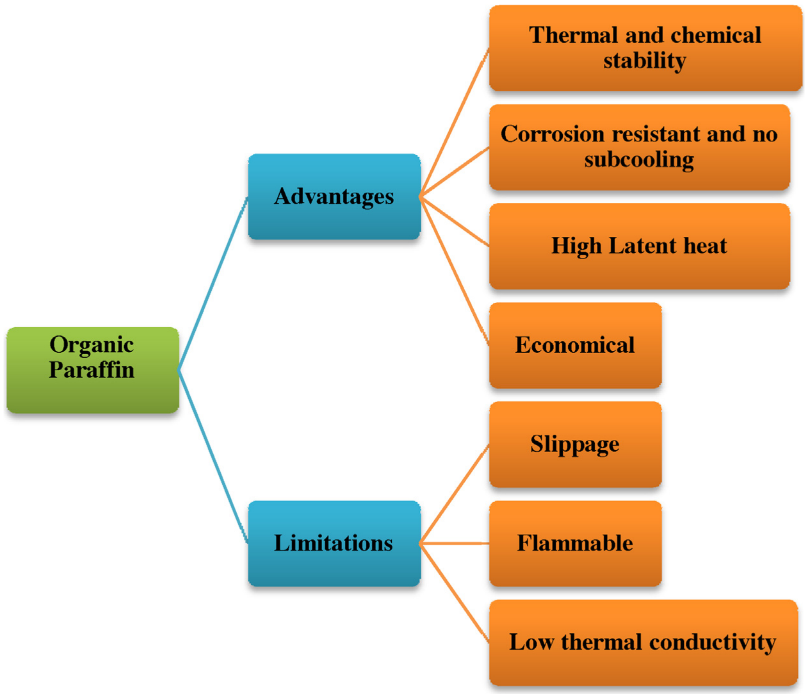

Fig. 5. Organic paraffin- advantages and limitations.

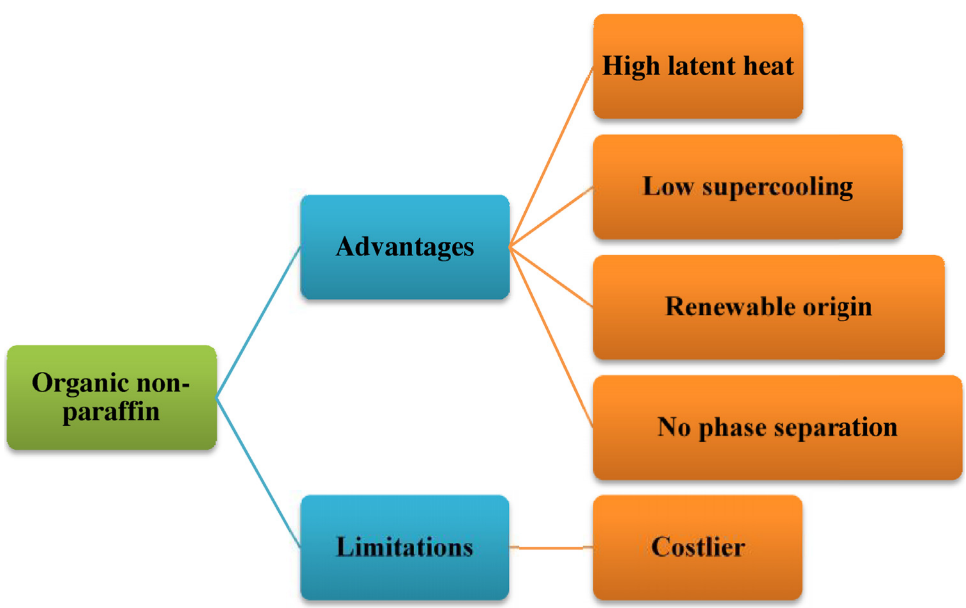

Fig. 6. Organic non-paraffin- advantages and limitations.

the storage or release of energy by absorbing or release of energy at a constant temperature by a phase change of material [9].

Phase change materials can be classified as organic, inorganic and eutectic materials. Organic materials include Paraffin and non-paraffins. The advantages and limitations associated with paraffins and non- paraffins can be understood from Figs. 5 and 6. It is known that paraffin has chain like structure ($CH_3 - (CH_2) - CH_3$), which releases the energy. The length of chain is an indication of latent heat of fusion and melting point. Melting point temperature range for paraffins is 12 °C–71 °C.

Apart from high latent heat, paraffins are corrosion-resistant and are free from sub-cooling. They are cheaper, reliable and chemically stable. Major limitations with paraffin include its low thermal conductivity, incompatibility with plastics, slipping from matrix, high volume changes to name a few. Non-paraffins generally include esters, glycols, and fatty acids. These materials generally possess dissimilar characteristics which provide choices to the user. The disadvantage with non-paraffins is their flammability limiting their application to lower temperature ranges.

However, fatty acids as phase change materials in buildings are gaining popularity because of high latent heat, no phase separation and low super cooling characteristics. Inorganic PCMs can be characterized as materials with high latent heat per unit mass and high thermal conductivity. The disadvantages of inorganic PCM are phase separation and incongruent phase change. Usually, the cost of inorganic PCMs is less than organic PCM. Eutectic means a com-

bination of two or more PCMs for tailoring the material according to the requirement. These materials are used when certain characteristics like specific melting points cannot be met by other PCMs [9].

The phase changes in phase change material can be from solid to liquid, solid to gas, liquid to gas and solid to solid. Solid to liquid transition gained popularity for application in various areas because of the disadvantages associated with other phase change processes. Liquid to gas transition involves handling of large volumes and high pressures making it impractical. Solid to solid transition, though compact in nature, provides low latent heat of fusion. Solid to gas transition also has the same problem as the liquid to gas transition [10].

Latent heat thermal energy storage can be classified based on storage medium as Ice thermal energy storage (ITES) and PCM based Thermal Energy Storage (TES). ITES refers to thermal storage system with ice in crystalline form or slurry as storage medium while PCM-TES involves PCM as storage medium. Though heat storage capacity of ice based TES is superior to PCM based TES, the volumetric heat storage density of PCM-TES is much higher than ITES. Moreover, PCM exhibits better thermo physical properties and phase change characteristics, no sub cooling, congruent phase change, good thermal stability and thermal reliability [11].

PCMs have been extensively used as storage medium for energy efficient heating, cooling, ventilation and air conditioning systems [12]. This indicates that PCM is proven thermal material for regulation of energy consumption. Therefore it is a potential candidate for passive thermal regulation in buildings.

It is a well-known fact that the energy storage capacity depends on parameters like specific heat in solid and liquid phases of PCM, weight of heat storage medium, temperature difference between initial state and melting states of PCM and temperature difference between melting state and final state of PCM [13]. Classification of thermal energy storage techniques available have been summarized in Fig. 4, the advantages and limitations of organic paraffins is also highlighted in Fig. 5 while organic non paraffins have been covered in Fig. 6 for quick reference.

3. Energy efficient construction of buildings

3.1. Thermally efficient materials

It is clear that as a consequence of rapid population growth coupled with improving living standards of people, the energy consumption is also on a constant rise. Researchers, over the years, tried finding the solution for this rising concern with different technologies. The idea of incorporating phase change material into different building elements gained importance as a result of this search. In this section, an attempt is being made to summarize the overview about various candidate PCMs, suitable to be incorporated in to the building elements.

It has been reported in the literature that including PCMs in building walls will decrease the mismatch between supply and demand of electricity [14]. PCMs are expected to decrease the temperature fluctuations in the buildings thereby enhancing the indoor thermal comfort. Using PCMs in buildings during winter will help in efficient utilization of solar energy. In summer, it helps in decreasing internal cooling loads.

If a building is viewed as a thermodynamic system, energy conservation across the building wall implies balance of energy generation within building, energy used by the users in the building, energy accumulated in the wall with PCM and energy transferred across the wall. This balance depends upon energy storage properties of PCM, the quantity of PCM and resistance to energy flow across the wall offered by PCM.

Table 1
Organic PCM properties (saturated and unsaturated) [8,13].

PCM	Phase transition temperature (°C)	Enthalpy of fusion (kJ/kg)
Propyl Palmitate	16–19	186
Glycerin	17.9	198.7
Hexadecane	18.1	236
Butyl Stearate	19	140
Paraffin ($C_{16}-C_{18}$)	20–22	152
Heptadecane	20.8–21.7	171–172
Dimethyl Sabacate	21	120–135
Paraffin C_{17}	21.7	213
Lactic acid	26	184
1-Dodecanol	26	200
Vinyl Stearate	27–29	122
Octadecane	28–28.1	244–250.7
Methyl Palmitate	29	205
Capric Acid	30.1	158
Caprylone	40	259
Camphenilone	39	205
MICRONAL 26	26	110
MICRONAL 5001	26	110
Acid Methyl Pentacosane	29	197
RT-20	22	172
Emerest 2325	20	134
Emerest 2326	20	139
Lithium Chloride Ethanolate	21	188

Table 2
Inorganic PCM (Hydrated Salts) properties [13].

PCM	Phase transition temperature (°C)	Enthalpy of fusion (kJ/kg)
$KF{\cdot}4H_2O$	18.5	231
$FeBr_3{\cdot}6H_2O$	21	105
$CaCl_2{\cdot}6H_2O$	29–30	171–192
$CaCl_2.12H_2O$	29.8	174
$LiNO_3{\cdot}3H_2O$	30	296
$Na_2SO_4.10H_2O$	31–32.4	251.1–254
$Na_2SO_4{\cdot}3H_2O$	32	251
$Na_2CO_3.10H_2O$	32–36	246.5–247
$CaBr_2{\cdot}6H_2O$	34	115.5
$LiBr_2{\cdot}2H_2O$	34	124
$FeCl_{3,}6H_2O$	37	223
$Na_2HPO_4.12H_2O$	35–36	265–281
$Mn(NO_3)_2{\cdot}6H_2O$	25.8	125.9

Table 3
Some eutectic PCM properties [13].

PCM	Phase change temperature (°C)	Enthalpy of fusion (kJ/kg)
Ga	30	80.9
Octadecane + docosane	25.5–27	203.8
Octadecane + heneicosane	25.8–26	173.93

Another important reason for inclusion of PCM in buildings is to decrease the use of heating and cooling devices in buildings during the peak hours of the day. Reason for choosing PCM among various thermal energy storage technologies has been reported in literature stating that for the same volume of PCM and sensible energy storage material, PCM will store 5–14 times more energy than sensible heat storage material [14].

Inappropriate PCMs, if used for building applications, might result in inefficient charging and discharging cycles of PCM. If the properties of melting point and Heat of fusion of PCMs lie within the temperature range of 18–40 °C, they may be deemed appropriate for building applications [15]. Critical thermal properties of organic PCMs, In-organic PCMs and Eutectic PCMs are summarized separately (Table 1, Table 2 and Table 3) respectively for reference.

Phase change materials can be included in construction materials through direct mixing or dipping into liquid PCM or mixing

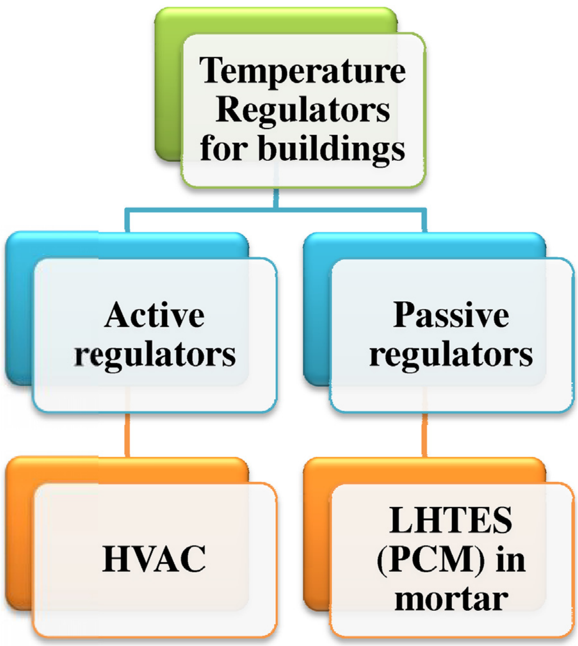

Fig. 7. Kinds of temperature regulators for buildings.

in the form of encapsulated micro and macro capsules in to the materials. Direct mixing involves mixing PCM and construction material in deigned proportions. Dipping the final form of building element into PCM is another alternative method wherein the PCM is adsorbed into the porous substrate. Encapsulation involves covering PCM with shells to prevent their leakage during phase change process. PCMs can be either microencapsulated or macroencapsulated.

Micro encapsulation involves covering PCM particles at micron level with polymer shells. Macro encapsulation involves confining the PCM in a container appropriate to the construction process and element being constructed. Shape stabilized PCMs and form stabilized PCMs are other viable alternatives for inclusion into construction materials (Fig. 7) when the thermal stability issue arises [15].

3.2. *Review of PCM- mortar combinations*

3.2.1. *Experimental trials of mortars with PCMs*

Mortar is typically a matrix formed by judiciously combining cement or any other cementitious material like lime or alkali activated binders with fine aggregates such as river sands or crusher rock powder or robo sand in the presence of adequate quantity of water. Sometimes, super plasticisers or viscosity modifying agents will also be mixed in the matric to improve the ease with which the mortar can be applied. Mortars are useful in bonding the bricks during the wall construction or plastering, both internally as well as externally as finishing layer. Mortar will have sufficient mechanical strength when the hydration reaction gets completed and calcium silicate hydrate gels are formed.

This hydration reaction gets affected when phase change material is directly mixed with cement mortar for energy efficiency. PCMs possess high heat storage capacity. This characteristic has been exploited in making of PCM induced mortars. But it has to be noted that inclusion of PCM into mortars might reduce the compressive strength of PCM composite.

For determining the thermal contribution of PCM in terms of heat release during hydration reaction, Eddhahak et al. [16] have used Langavant-type semi adiabatic method. In this work, heat flux from the PCM mortar was determined through numerical diffuse element method by examining different PCM mortar combinations. It was found during this work that, PCM mortars release lower heat when compared to mortar alone and hydration reaction gets clearly affected with PCM inclusion. Moreover, it may be noted that mortars with damaged PCMs require more time for hydration reaction to be completed when compared to mortars with non-damaged PCMs.

Sharifi et al. [17] have experimented with Rice Husk Ash aggregates and the light weight aggregates by soaking them with PCM before being mixed with other ingredients of mortar. There was an observed compromise in the form of reduction in compressive strength by 10% for the Light weight aggregate case and 35% for the Rice Husk Ash aggregate particles. Chemical decomposition of the hydration products was not observed during these experiments. However, it was reported that PCM leakage was observed during these tests.

Kang et al. [18] experimented with bio based PCMs as a thermal enhancing material in mortars in combination with silica fume and exfoliated graphite nanoplatelets. It was experimentally found that Bio based PCM (containing fatty acids) with silica fume and with silica fume & graphite nano platelets have got their respective thermal conductivities increased by 156% and 243% when compared with mixes prepared with bio-based PCM alone.

This organic PCM was made from underutilized feedstock and is renewable in nature. It has alpha- linolenic acid in it. Silica fume is cost effective additive when viewed from its performance perspectiveand is a lightweight admixture. Exfoliated graphite nanoplatelets are added to improve thermal conductivity. This composite was made by vacuum impregnation method. Fig. 8 indicates that thermal decomposition of bio-based PCM started earlier than Bio based PCM added with silica fume and with silica fume and graphite nanoplatelets indicating that latter composites are stable when compared with bio-based PCM.

From Fig. 8, it could also be inferred that phase change for bio based PCM in combination with silica and with silica and graphite nanoplatelets took place in a narrow temperature range indicating supercooling characteristic of Bio based PCM.

Vieira et al. [19] have carried out a detailed study with PCM and other admixtures like titanium nano particles and superabsorbant polymer with mortar. Superabsorbent polymer had high hygroscopic capacity. This was suppressed in the presence of PCM because PCM cannot retain water in it. Therefore there was a decrease in the apparent density of the sample. Nano titanium particles are added to clean the atmosphere by photo catalytic degradation.

The particles of PCM have strong cohesion but this did not affect the fluidity of the mortar sample because of the spherical shape of particles. The low friction among particles is also because of the same reason. The composite mortar was compared with reference mortar which has no additives. It can be seen from Fig. 9, wherein the thermal conductivities obtained by the research team were presented, that the mortar with no additives has good thermal conductivity while mortar with PCM has good insulation properties.

Sakulich et al. [20] have found that freezing and expansion of concrete wall can be inhibited by incorporating PCM in the mortar. This is because of its energy storage and release capability during melting and freezing phases. Freezing and expansion due to temperature disturbance is important because it controls the service life of building walls. During this work, mortars made with river sands have outperformed when compared with the mortars prepared with light weight aggregates in this study.

The porous nature of the light weight aggregates and the reduced packing efficiency with light weight aggregates have been attributed for the reduced strength of mortars. It was also observed that the paraffin wax based phase change material do not disturb

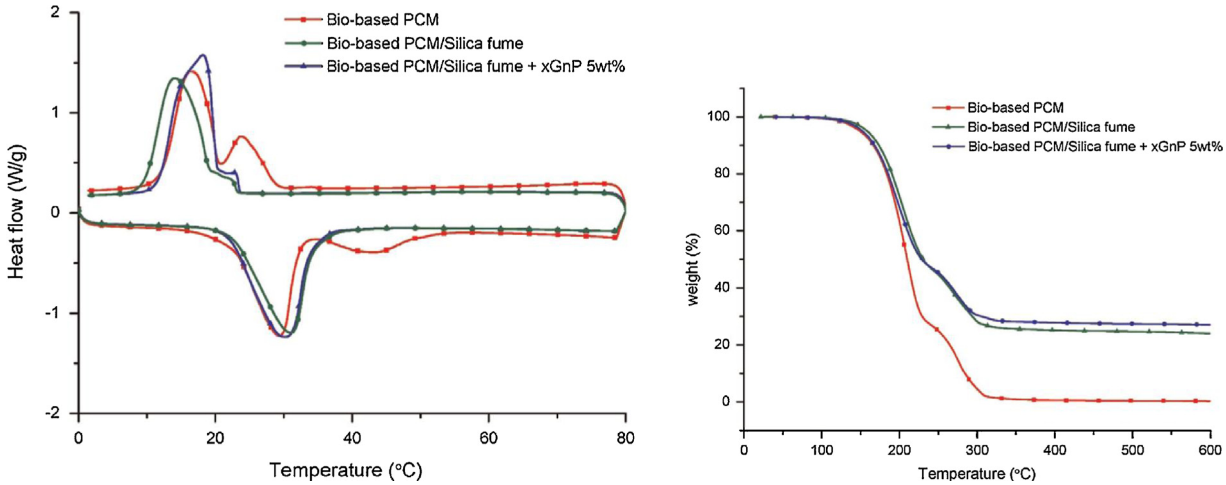

Fig. 8. DSC and TGA results for combination of bio based fatty acid with silica fume and graphite nanoplatelets [18].

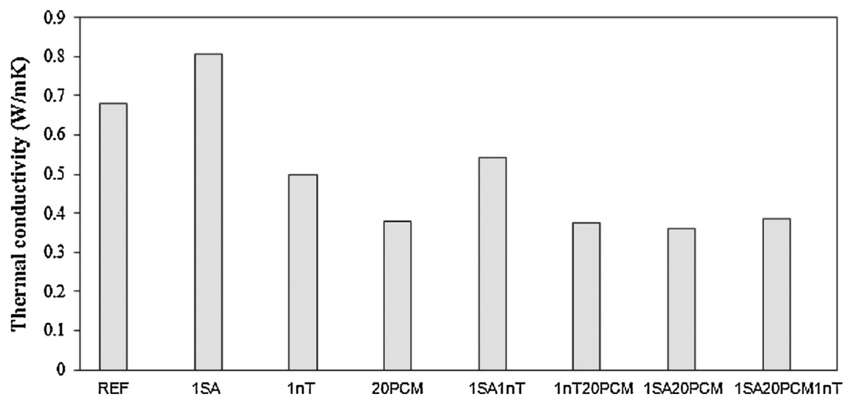

Fig. 9. Thermal conductivity variation for reference mortar (REF), 1% superabsorbent polymer (1SA), 1% titanium nano particles (1nT), 20% PCM (20PCM) and any combination of these [16].

the hydration reaction of mortar. Light weight aggregate with silica fume was observed to be the better performer during this study.

Ventolà et al. [21] found that the mineralogical phases of lime mortar remain unaltered when PCM is added, making lime mortar with PCM a viable alternative in place of conventional cement mortar for improved energy efficiency. Zhang et al. [22] found that n-octadecane/expanded graphite composite phase change material had all the desirable properties, a mortar would like to have for good performance. The costly micro encapsulated PCMs were suggested to be not really viable in this study due to their high costs.

An experimental study, carried out by Meshgin et al. [23] revealed that failure pattern of PCM embedded mortar is different from the rubber particles embedded mortar. PCM embedded mortars have sudden brittle failure while rubber based mortar has gradual failure. The brittle failure of PCM embedded mortars is attributed to the spherical encapsulation of mortars. While rubber particles required the usage of re dispersible polymer powder for bond strength, PCM embedded mortar did not require any such additive. Good bond strength of PCM embedded mortars can be attributed to smaller size of particles of PCM (17–20 μm).

In terms of thermal conductivity, PCM embedded mortars have been observed to be superior than rubber particles embedded mortar. Drying shrinkage is another aspect which is of prime importance and is very little for PCM embedded mortars when compared to rubber based mortars for the same volume fraction.

Han et al. [24] have experimented with carbon nanotubes and Micronal DS 5000X as a additives to the cement mortars. During this study, micro encapsulated PCMs were used to improve the compatibility and reduce the leakage. Microencapsulated PCM was induced into cement composite in liquid form for homogeneity in the composite. The experiment involved comparison of cement composite with and without PCM/CNT. The result was a temperature difference of 6.8 °C in the building models built with PCM/CNT. This indicates that inclusion of PCM/CNT clearly contributes to the energy efficiency of buildings. Carboxyl multiwall CNT helped in overcoming the problem of low compressive strength and thermal conductivity when only PCM was used.

Paraffin was impregnated into expanded graphite and diatomite and a composite PCM was developed and used as a constituent material to enhance the mortar properties in an experimental work reported by Li and Wu [25]. Graphite was found to be advantageous due to its uniform distribution in PCM and zero chemical affinity/reactivity. The optimum proportion of paraffin and diatomite was found to be 70:30. The graphite has improved the thermal conductivity of PCM-mortar. However, latent heat of fusion got reduced for the modified mortar matrix. Increase in thermal conductivity was found to be 32.3% with 1% PCM and 8% graphite.

He et al. [26] have tried the combination of capric acid and myristic acid, a eutectic PCM, impregnated in to expanded perlite, as an admixture in cement mortar. This composite PCM was encapsulated with paraffin for 60% mass fraction to control the leakage within 3%. Expanded perlite acted like supportive material by holding PCM due to capillary forces. This PCM addition has increased the time to attain maximum temperature thus resulting in optimum temperature regulation of the room. The physical and mechanical

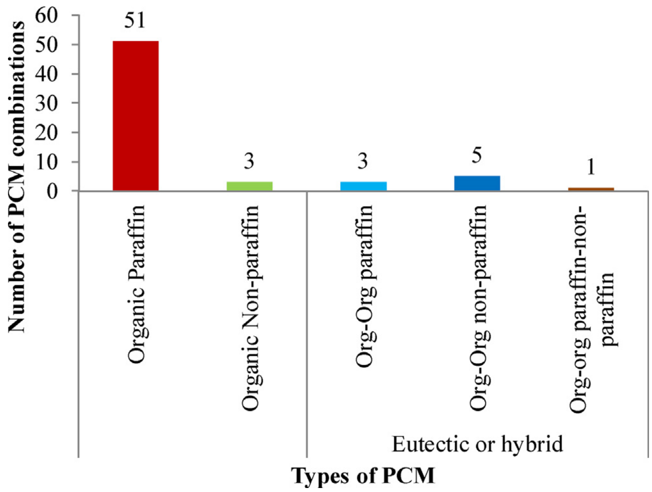

Fig. 10. Preference of PCMs for inclusion in mortar (2010–2017).

properties were found to be sufficient for usage as binder materials in buildings.

Tie-lin et al. [27] have attempted the usage of stearic acid-paraffin based PCMs in waste aerated autoclaved concrete, which had enough pores in its internal structure to hold the PCMs. This experiment has demonstrated the usage of waste material and effectively converting in to a green product with the introduction of composite PCM. This study has reported good stable mix and enhanced thermal performance, critical for building environment.

The popularity of different types of PCMs being used in Mortars along with types of mortars being tried in combination with PCMs is presented in Figs. 10 and 11 for quick reference.

3.2.2. Inclusion of encapsulated phase change materials in mortar

In the previous sub-section, case studies involving direct incorporation of PCMs in the mortars have been discussed. Looking at a few difficulties encountered with direct inclusion of PCMs in mortars, researchers tried with micro and macro encapsulated PCMs. This ensured that the PCM leakages are completely controlled. In addition, it also resulted in better heat transfer, chemical compatibility and also noninterference with hydration kinetics of the mortar. One general observation in all these attempts is that the encapsulated PCMs make the product expensive. However, life cycle analysis, if done might bring out the clear picture on this front. A summary of attempts with encapsulated PCMs in mortars is presented in Table 4 for ready reference.

It has been generally observed by almost all the researchers that the micro encapsulated PCMs have resulted in lower thermal conductivity, thus leading to poorer thermal response. However, the mechanical strength rarely gets affected with the inclusion of encapsulated PCMs since the proportion of PCMs in the mortar is very low.

Usually micro encapsulation involves covering the phase change materials with spherical polymer shells. This can be achieved by physical and chemical means. Physical methods include spray drying, centrifugal process and fluidized beds while the chemical methods include interfacial polymerization, in situ polymerization, simple or complex coacervation, phase separation, suspension like polymerization etc.

Coacervation and emulsion based polymerization are best suited for phase change material encapsulation in microscopic form. The selection of method of encapsulation is usually based on material dimension (in μm) and the composition of PCM to be used. It has been reported in the literature that paraffins, fatty acids are generally encapsulated by coacervation, in situ polymerization, interfacial poly-condensation and sol-gel methods. It may be noted that coacervation, suspension like polymerization, sol-gel, spray drying and emulsion polymerization are most widely used for building applications [36].

3.3. Thermal and mechanical properties of PCM embedded mortars

The following section contains information on different research studies conducted to determine the optimum PCM-mortar combinations primarily based on their thermal and mechanical properties.

Form stable PCMs have the capability to improve thermal performance of buildings. However, they tend to be hydrophilic in nature thus leading to leakage. The supporting material in this PCM reacts with water and leaves the PCM aside when it comes in contact with water in liquid state. To resolve this issue, Ramakrishnan et al. [37] tried impregnating the paraffic PCM with hydrophobic expanded perlite.

Hydrophobic Expanded perlite absorbs PCM to higher extent (50%) when it is vacuum impregnated while the absorption of PCM remains same for expanded perlite with no coating. Hydrophobic expanded perlite has good bondage with mortar because of irregular microscopic structure. PCM leakage was found when uncoated expanded perlite-PCM was incorporated into concrete/mortar after hardening while that was not found with hydrophobic expanded perlite.

As can be seen from Fig. 12, thermal performance of the expanded perlite with hydrophobic coating based PCM composite was assessed by comparison with reference panel with no PCM also with chamber temperature profile being imposed over these two profiles. The thermal inertia of EP-PCM composite was high which was concluded from the high temperature difference between indoors and outdoors. Thermal storage rate was also found high for the composite studied when compared to reference panel and the internal flux variation examination revealed that temperature fluctuations came down by using this composite. Thermal stability analysis was conducted for 100 cycles and it was found that there was no change in thermal behavior at the end.

Micro capsules of PCM generally have poor thermal conductivity because of the polymer shell in which they are enclosed. To improve thermal conductivity, hybrid polymer shells can be used. Zhang et al. [38] have experimented doping graphite flakes into paraffin wax based micro capsules by interfacial condensation. As the graphite based PCM content is increased, it resulted in improved thermal storage capacity of building entity and resulted in attenuation of temperature fluctuations. However, there was a marked reduction in the structural properties of the mortar matrix.

Fig. 13 represents DSC results for micro encapsulated PCM with graphite dispersion on it. Along with this, DSC results for PCM based cement composites were also presented. The results indicate that PCM with graphite flakes has higher heat capacity than other cement based PCM composites.

PCMs generally have high thermal inertia. This property helps preventing sudden cooling and sudden heating of structures. Sharifi et al. [39] have highlighted this aspect in their research findings. A comparative study with three different PCM impregnated in Lightweight aggregates (LWA) was carried out during this study.

A comparative study of three different form-stable composite PCM for building applications was reported by A. Karaipekli et al. [40]. The idea was to impregnate the selected PCM into pumice which is naturally occurring pozzolan that has non-crystalline structure with pores. Pumice has very low density, high porosity, large surface area, and little chemical affinity. This makes it a potential candidate for absorption of PCM through surface tension and capillary forces effectively and at very low cost of preparation.

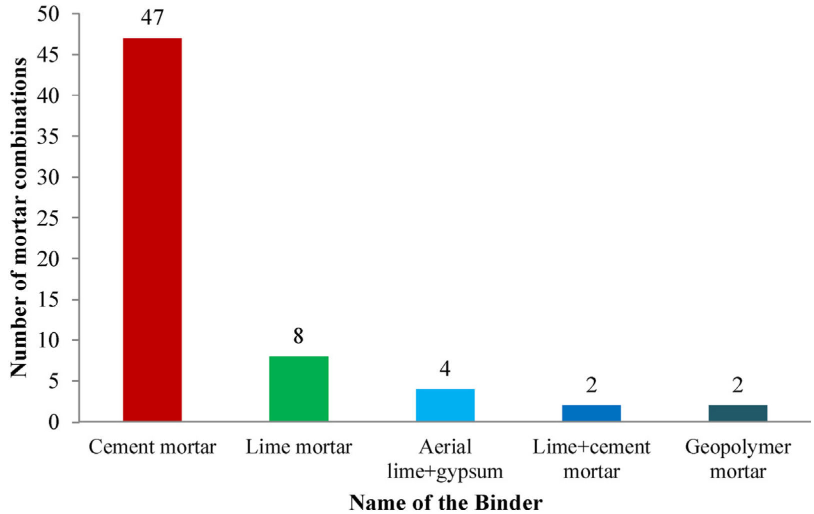

Fig. 11. Types of mortars tried with PCMs (2010–2017).

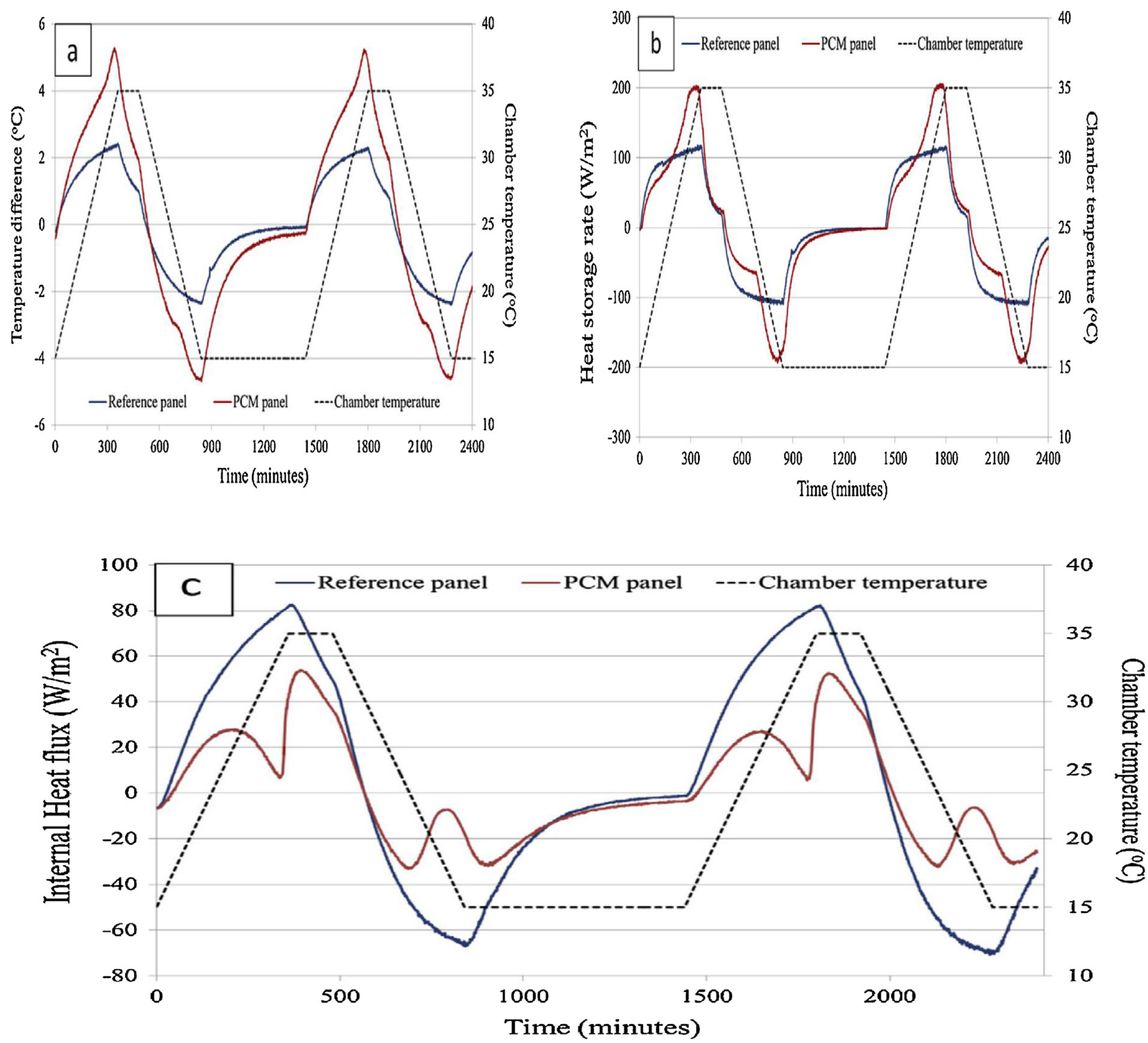

Fig. 12. Thermal characteristics of hydrophobic expanded perlite-PCM-concrete compared with panel with no PCM (a,b,c) [37].

PCMs considered during this research study are capric acid-palmatic acid eutectic mixture, dodeconol and heptadecane. The research involved characterization of these composites in terms of thermal properties, chemical stability, thermal stability, ther-

Table 4
Research Summary of Microencapsulated PCM based mortar.

Encapsulation and PCM	Objective	Observations	Reference
Microencapsulated Paraffin	To study the ability of PCM to mitigate thermal strains and their effect on mechanical properties of concrete	PCM is effective in enhancing thermal performance but decreases the compressive strength in PCM based concrete composites. Apart from this, PCM are effective in thermal cracks inhibition for temporary period. Setting time of concrete increases with PCM inclusion.	Snoeck et al. [28]
Microencapsulated Paraffin	To study the effect of coating plaster with PCM on thermal performance and mechanical properties of concrete structures in Algeria	Deterioration of mechanical properties with PCM was observed. 70% plaster and 30% PCM is the optimum combination as concluded in the experimental study for buildings. Effective in thermal performance enhancement in winter and summer for Algerian climate	Derradji et al. [29]
Microencapsulated Paraffin	Comparative study of two different PCM microcapsules and their effect on shrinkage of lime-gypsum mortar	Shrinkage of PCM-mortar is a strong function of encapsulating material. Increase in water requirement with PCM for good workability. Polymethylacrylate is better than melamine-formaldehyde encapsulation in terms of mechanical properties.60% lime with 40% gypsum and 20% PCM is the optimum combination for both polymeric capsules. Fiber along with mortar-PCM composite provides better tradeoff between mechanical and thermal properties	Cunha et al. [30]
Microencapsulated Paraffin PCM	Microscopic study of thermal and mechanical properties of microencapsulated single layered PCM mortars along with fire propagation resistance determination	Increased requirement of water for hydration and to maintain workability with single layered mortars at setting stage. Thermal properties of the mortar improved. 10% PCM inclusion is the optimum as reported by authors with mitigation of compressive strength by 5%. Homogenous distribution of microcapsules was found through microscopic study. Organic PCM are not good candidates for fire resistance but possess good fire extinguishing features.	Haurie et al. [31]
Microencapsulated Paraffin	Comparative study of two microencapsulated PCM to determine their influence on composite cement mortar using FEM simulations	PCM with aggregates of 5 μm was not distributed uniformly when compared to another PCM whose particles mean size is of 7 μm. 2D plane strain model was used to determine interfacial interaction of PCM and cement paste. For PCM with aggregates, there was continuous decrease in compressive and flexural strengths.	Aguayo et al. [32]
Microencapsulated PCM	To determine thermal characteristics of PCM using fluxmeters as DSC based measurements are not able to completely represent characteristics of heterogenous composite such as PCM-mortar. To develop a numerical model and try to match its results with published results	PCM-mortar combination is able to control the indoor temperature fluctuations. The numerical model represents the physical model with reasonable accuracy. To get accurate phase change temperature of PCM, it is necessary to decrease the heating rate but the time required for characterization will be large.	Kousksou et al. [33]
Macroencapsulated Paraffin PCM	To study the effectiveness of incorporating lightweight aggregate with macroencapsulated PCM in concrete through indoor and outdoor tests. To also determine the compressive strength and shrinkage strain of LWA-PCM. To assess performance of this composite utility by using in floor of a building in Hong Kong	LWA-PCM-concrete is found suitable for structural applications as compressive strength was found to be greater than 15 MPa after 28 days. The shrinkage strain reduces as the amount of macro encapsulated PCM in the LWA increases. Indoor test indicate reduction in temperature fluctuations and shift in energy consumption from peak periods. Outdoor test indicate optimum performance when the temperature difference between day and night is high. Economic analysis of PCM combination has shown return on investment in 29 years. Decrease in CO2 emissions by 465kg-eq/year was found	Memon et al. [34]
Micro encapsulated Paraffin PCM	To determine changes in thermal and mechanical properties of lime-gypsum mortar (60% aerial lime and 40% gypsum) incorporated with micro encapsulated PCM	The results revealed that usage of fiber and gypsum avoided cracks. Workability increased with increased water content. Compressive and flexural strength increased with PCM content. The temperature fluctuations decreased and delay of temperature rise by 2.5 h has been observed compared to the case without PCM.	Cunha et al. [35]

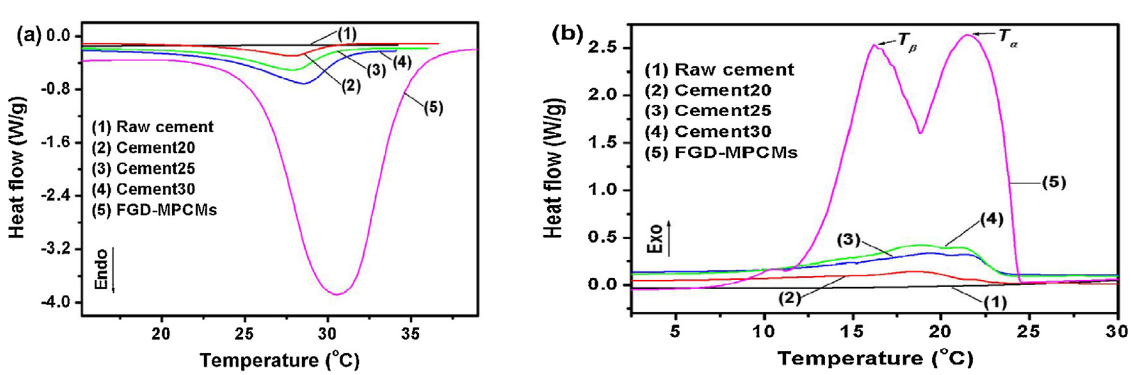

Fig. 13. DSC results for different proportions of graphite flakes doped into cement mortar [melting-left and freezing-right] [38].

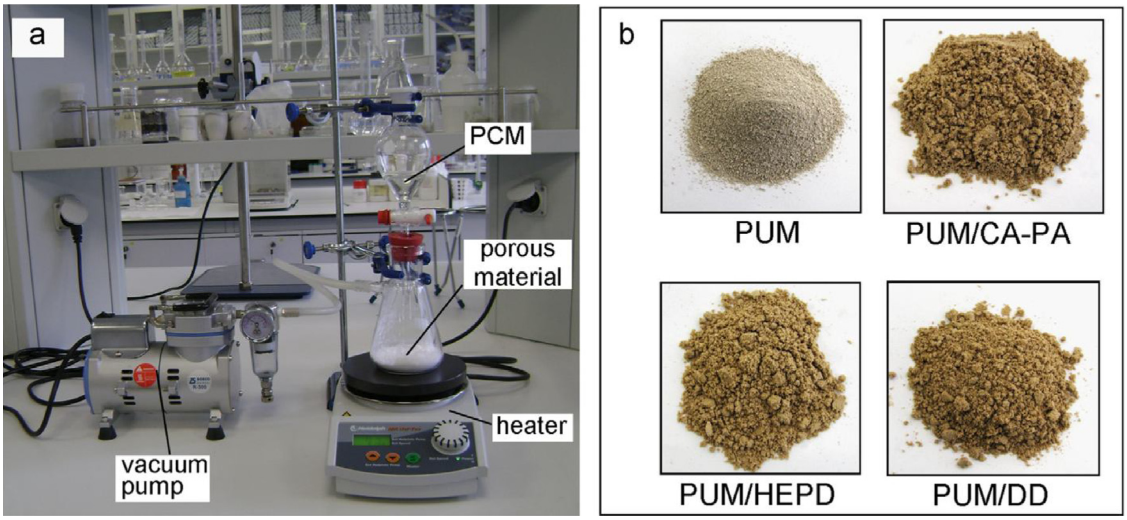

Fig. 14. Vacuum impregnation setup and various form stable composite PCM along with pumice (CA-PA-Capric acid and Palmitic acid, HEPD-Heptadecane, DD-Dodecanol) [40].

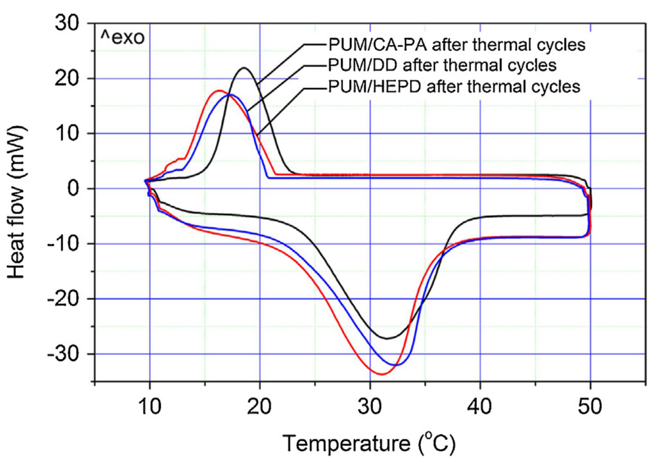

Fig. 15. DSC curves for different form stable composite PCM after few thermal cycles [37].

mal cycling stability and microscopic view before and after impregnation. The vacuum impregnation method was followed for impregnation of PCM.

Fig. 14 gives a pictographic view of the vacuum impregnation setup used during this research along with images of few pumice-PCM samples. It was reported that the PCM do not react with carrier material except for some interactions between PCM and the carrier. The morphology was studied through scanning electron microscope (SEM) images. Thermogravimetric analysis was carried out to determine the thermal stability of PCM composite. The PCM composite was tested for 3000 thermal cycles of phase transition from solid to liquid state and vice versa. The cycling results revealed no degradation in thermal performance of the composite PCM over the spectrum considered.

The DSC based tests revealed that the composite PCM are suitable for 21–23 °C temperature range applications. From Fig. 15, which represent DSC results after few thermal cycles, it can be seen that the changes in phase change temperature is minimal. The comparison of thermograms from DSC of pure PCM and composite PCM revealed that there were little changes in phase transition temperatures of composite PCM and pure PCM while enthalpy of fusion varied by substantial extent. It was reported in this research that pumice-heptadecane composite PCM is relatively superior due to its thermal performance [40].

S. Cunha et al. [41] have investigated the effect of high temperature stimulus to mortar with and without PCM. The PCM used was microencapsulated paraffin but the mortars studied were aerial lime, hydraulic lime, gypsum and cement. The PCM percentages examined were 0% and 40% (12 variations in mortar compositions) at different temperatures. Flexural and compressive strengths were determined by using standard testing protocols. The tests revealed that for the reference mortar (0% PCM) and for mortar with PCM for all kind of binders, there was decrease in mechanical strength with increasing temperature. Aerial lime is found to be more sensitive while hydraulic lime was least sensitive to high temperatures. High temperatures generally lead to thermal stresses and finally lead to thermal cracking. The cracks in their microscopic form were observed during this research.

Eddhahak-Ouni et al. [42] have reported an experimental investigation which they have carried out with micro encapsulated PCM into Portland Cement Concrete/mortar. Thermal inertia of concrete increased with PCM inclusion. At the same time, there was a reduction in mechanical strength as reported in this research work. Through artificial ageing, thermal properties before and after some age were compared. The results indicated that thermal response remained unchanged even when the age increased for the PCM-concrete. A good correlation has been noticed between homogenization approach to evaluate thermal conductivity and experimental approach to determine thermal conductivity using hot disk.

M. Kheradmand et al. [43] have studied thermal interactions of organic paraffin based PCMs incorporated in mortars. It was that there is no thermal interaction between individual PCM when micro encapsulated hybrid PCM was incorporated in mortar. Three PCM samples were considered with transition temperatures ranging from 18 °C to 28 °C. It has also been found that when hybrid PCM is included in mortar in microencapsulated form, the resultant hybrid PCM's transition temperature is half of one of the parent PCM. This was ascertained by superimposing DSC thermograms of individual PCM over the thermograms of hybrid PCM. From DSC tests, specific enthalpy was also found.

Z. Pavlík et al. [44] have carried out an experimental investigation on the lime based plastering mortar with PCM as an additive to improve the thermal storage properties. The PCM considered was paraffinic wax in micro encapsulated form in polymer shells. It has been found that the compressive strength of the lime based plaster with PCM is higher than ordinary lime plaster. The specific heat

capacity and water absorption coefficient were found to be superior for regulation of indoor temperature of an enclosed space.

The compressive strength of lime plaster without PCM was 3.9 MPa while that for the case with PCM was found to be 4.9 MPa. The moisture holding capacity of the lime based plaster with PCM was found to be less that the mix without PCM, making it a very good thermal regulator. It was also found that the thermal conductivity of lime based plaster with PCM was higher than ordinary lime plaster which again is good indication of faster energy transit from the material and to the material. It was also found that the phase change temperature was near the desirable room temperature.

S. Drissi et al. [45] have compared thermal properties of damaged and non damaged PCMs. It has been observed that damaged PCMs possess specific heat capacity lesser than non-damaged PCMs by 28%.In this research, fast approximate method has been proposed using which heat capacity of PCMs can be determined by direct exploitation of heat flux curves obtained through DSC after scanning PCMs at different heating rates. It can be understood from the results of this research that heating rates for DSC should be as low as possible for maintaining thermodynamic equilibrium.

Joulin et al. [46] have studied the heat transfer characteristics of micro encapsulated PCM integrated into cement mortar vis-à-vis the cement mortar without PCM. The results have indicated decrease in thermal conductivity of PCM based cement mortar but the latent heat and specific heat capacity were found to be sufficient for building applications [46].

Thiele et al. [47]. have identified a new performance criterion to compare different PCM-mortar composites to arrive at best passive energy solution. It was named as energy indicator (figure of merit) by the authors. The main reason quoted for introducing new criterion was that the available experimental procedures to compare the effectiveness of PCM-mortar composites in reducing the energy consumption are time consuming and material consuming in nature.

The energy indicator or figure of merit based determination of temperature at the centerline of a cylindrical specimen was in confirmation with the experimental and numerical predictions. Here, the specimen considered was PCM composite with PCM incorporated in microencapsulated form. It was also found that the energy indicator is sensitive to the parameters of interest such as the volume fraction of PCM. The energy indicator increases with PCM volume fraction and latent heat of fusion but decreases with increase in thermal conductivity.

PCM is used in radiant floor systems to enhance its thermal storage capacity. A comparative study of different mass fractions of PCM in the composite is considered for fire behavior determination. It has been found in this study that there was a decrease in thermal conductivity, thermal diffusivity in the PCM composite which is indicative of its thermal storage capacity. In order to determine fire behavior, dripping test, smoke test and pyrolysis calorimeter for flammability were conducted. The results indicated that increase in PCM is detrimental to the fire behavior of PCM-mortar composite but the damage is not high and the basic requirement of thermal storage is not highly effected. Hence, it can be deduced that the fire behavior of PCM composite has to be ensured in every study involving PCM −mortar composites [48].

Lucas et al. [49] have conducted the characterization studies of PCM added to lime mortar. The results primarily indicated that the lime mortar, generally used in rehabilitation of old buildings, did not lose its mechanical strength by addition of PCM. However, added PCM has resulted in energy consumption in buildings. During this study, PCM was incorporated in to the mortar in micro encapsulated form. The characterization included determination of porosity, mechanical strength and microstructure. The composite with 20% PCM by weight was found to be superior to the one with 10%. The lime mortar with 10% PCM by weight has high porosity and reduced mechanical strength than the mortar without PCM while the matrix with 20% PCM by weight has higher porosity than ordinary mortar.

A study to determine the heat storage characteristics of a composite PCM incorporated in cement mortar has been reported by Cui et al. [50]. The PCM used during this study was paraffin which was absorbed into expanded graphite by vacuum absorption method. This method is cheaper than encapsulation method. Moreover, this PCM composite has higher thermal conductivity than encapsulated PCM and the PCM itself. It has been found that with increasing PCM content, the mechanical strength kept on reducing.

It was concluded that 20% PCM combination has resulted in a mortar suitable for building applications The heat storage coefficient for composite PCM based mortar is 1.74 times the ordinary mortar indicating the superior heat storage property of PCM based mortar. The transition temperature and latent heat decreased after the PCM is included in the expanded graphite. But that does not restrain its use in buildings for energy storage. The reason for not using PCM directly could be due to the presence of leakage issues during phase transition and low thermal conductivity especially for paraffin PCMs (Fig. 16).

Tittelein et al. [51] have demonstrated that inverse methods of heat transfer could be used to determine the thermo physical properties of interest for thermal behavior characterization. For this, experimental measurements were taken using flux meters attached at either ends of the sample. An alternative method of developing enthalpy curve without the DSC measurements was demonstrated during this study. Sensitivity analysis was also carried out to determine the influential parameters for the energy transfer during phase change. The sensitivity analysis relied on the assumption that the energy transfer is symmetric in nature which is not the case in reality.

The utility of bio-based fatty acids as thermal energy storage material has been investigated and reported by Cellat et al. [52]. The bio based fatty acids are obtained from animal and vegetable oils in contrast to paraffins which are obtained from non-renewable fossil fuels. The organic chemical compounds considered are capric acid (CA), myristic acid (MA), lauric acid (LA) and palmitic acid (PA). Based on the desired indoor temperatures (22–27 °C), twelve binary mixtures were prepared and their thermal characteristics were compared and finally CA-LA and CA-MA combinations were considered for incorporation into concrete for its thermal inertia enhancement based on latent heat and phase transition temperatures from DSC measurements. The DSC curves obtained during this study are presented in Fig. 17 for composite PCM, for ready reference. In addition, the mechanical strengths obtained during the study were presented in Fig. 18.

The results of thermal and mechanical characterization revealed that these PCMs can be used for building applications. The mechanical tests revealed that the compressive strengths decreased as the PCM content is increased which can be attributed to weak interfacial bonding of PCM with cement particles. Thermo gravimetric analyses revealed that the degradation of the PCM starts at 120 °C. The latent heat of fusion for CA-LA and CA-MA are 109 and 155.4 J/g respectively. It has also been stated that these fatty acids possess flammability lower than paraffin. The mass fractions of PCM considered for analysis are 1 and 2% by wt. It has also been reported that the hardening time of the concrete reduces considerably if these PCMs are incorporated into it.

Wang et al. [53] have reported that paraffin, as PCM, can be impregnated in expanded perlite as supporting matrix and can be incorporated in clay geopolymer mortar for improved thermal and mechanical properties of the mortar so that the indoor temperatures can be regulated especially in rural regions. The experimentation involved comparison of clay geo polymer mortar incorporated with expanded perlite alone; expanded perlite

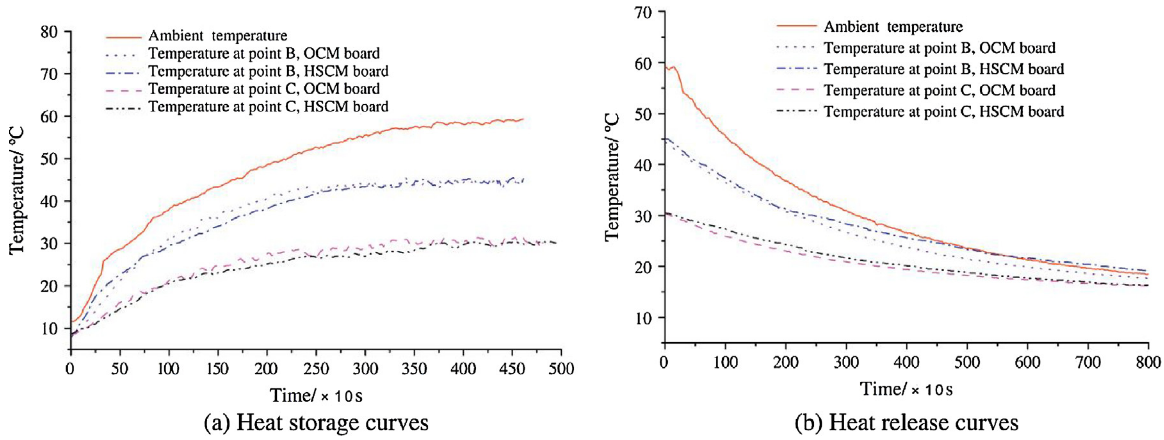

Fig. 16. Temperature versus time curves for charging and discharging for reference mortar (cement mortar) and PCM-mortar [50].

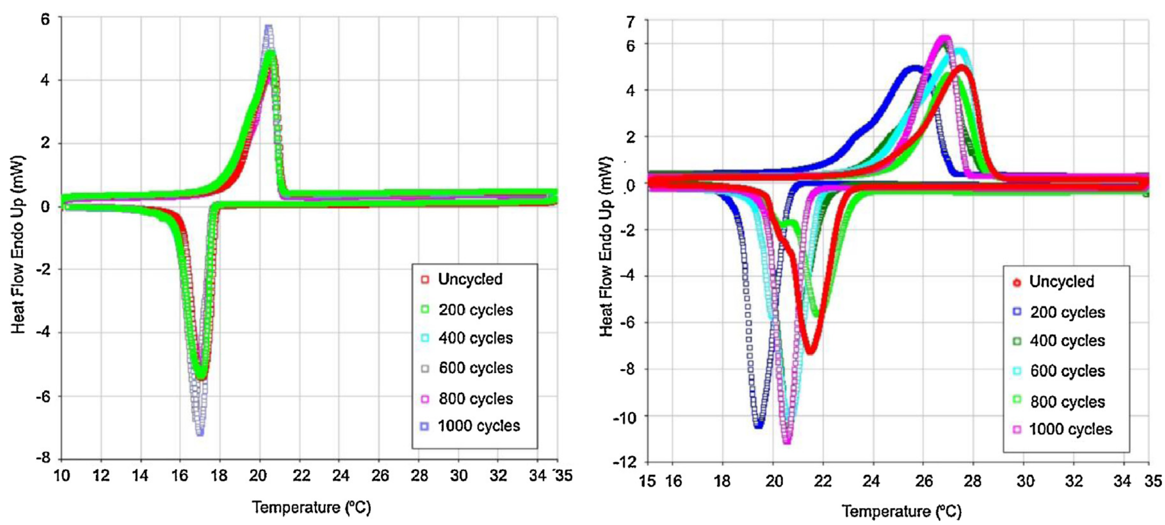

Fig. 17. DSC curves for different number of thermal cycles-CA-LA (left) and CA-MA (right) [52].

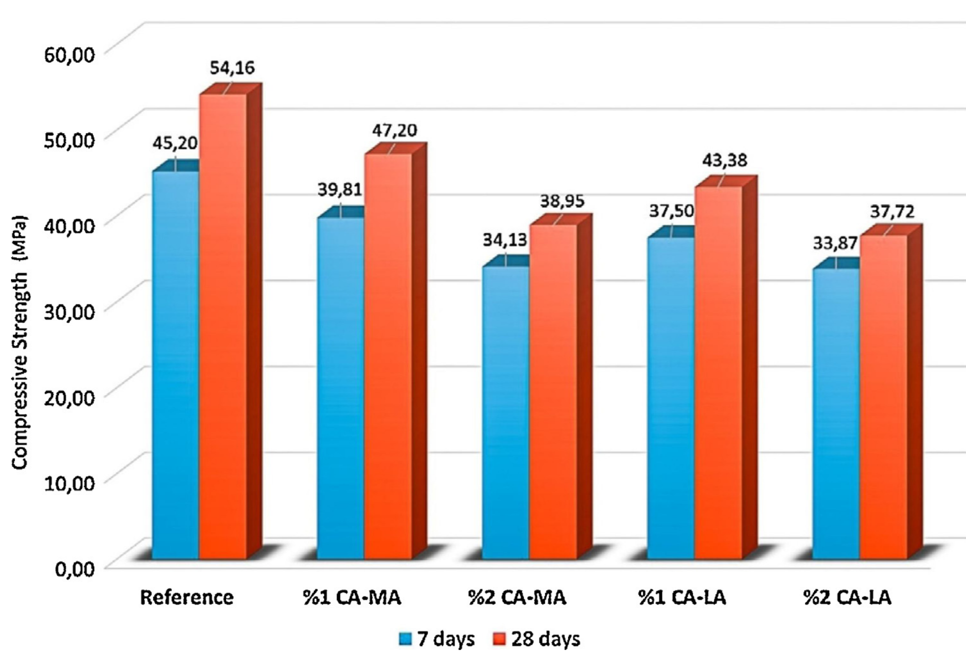

Fig. 18. Compressive strength of bio-based fatty acid based concrete mixtures [52].

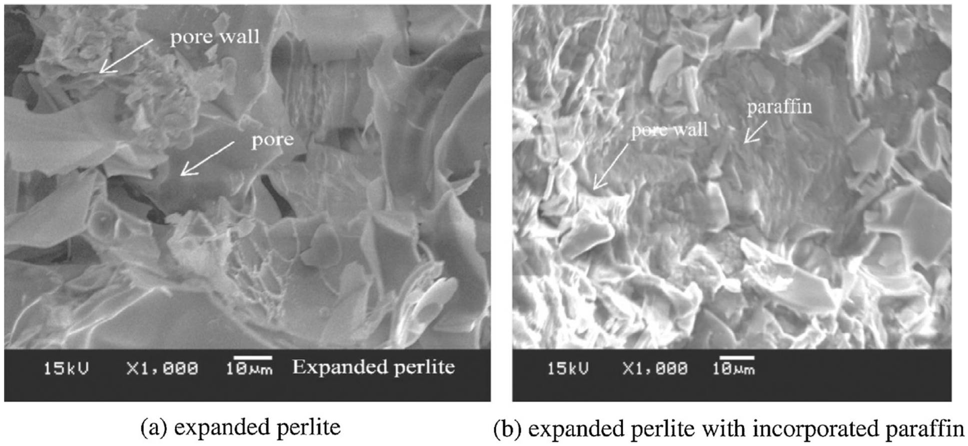

Fig. 19. SEM images of expanded perlite and paraffin-expanded perlite [53].

impregnated with paraffin and expanded perlite impregnated with paraffin and encapsulated by calcium silicate. The encapsulation prevented leakage of PCM during phase change. The paraffin was impregnated by vacuum absorption method into perlite while the PCM was incorporated into mortar by vacuum adsorption method.

The results indicate that the mechanical properties like compressive strength increased for encapsulated paraffin based mortar and paraffin impregnated into perlite when compared to expanded perlite based mortar. The reason for superior properties of expanded perlite and paraffin combination were attributed to low surface tension of paraffin and good adhesion between expanded perlite and paraffin. The SEM images, as reproduced in Fig. 19 indicate that expanded perlite has many pores and it helped PCM to be absorbed and after absorption, few failure surfaces of PCM-expanded perlite can be observed. The clay geo polymer mortar is prepared by mixing clay with slag from blast furnace and then an alkali activator is added. This mortar is best suited for cheaper constructions.

In yet another study carried out by Cunha et al. [54], comparison of thermal and mechanical behaviors of lime-gypsum mortars with two different micro encapsulations has been done. The encapsulating materials are polymethyl metha acrylate and melamine-formaldehyde with the PCM being paraffin and their respective transition temperatures and phase change enthalpies are found to be 22.5 °C and 110 kJ/kg and 22.5 °C and 147.9 kJ/kg.

The encapsulations differed in roughness (polymethyl metha acrylate being rougher than melamine-formaldehyde) which ultimately affected the shrinkage property depending upon the water content absorbed for better workability. Polymethyl metha acrylate based PCM absorbed more water than melamine-formaldehyde based PCM thereby; the shrinkage was observed.

The addition of gypsum and polyamide fibers helped in controlling shrinkage as reported in the literature. For compressive and flexural strengths, the polymethyl metha acrylate based PCM was found to be superior. The optimum PCM mass fraction was found to be between 15 and 20% for the samples examined. Increased PCM content increased the porosity and it resulted in inferior mechanical properties.

An attempt has been made to correlate micro structure with the mechanical strength behavior of the PCM – Mortar combinations by Lucas et al. [55]. In this work, four different combinations of lime mortar, lime-cement mortar, lime-gypsum mortar and cement mortar with PCM micro capsules have been investigated. The micro capsules were found to be spherical through Scanning electron microscopy (SEM). This shape aided in reduction of particle to particle friction and improved workability. It was also found that the reduced macro porosity has contributed to the mechanical strength of mortar.

However, for cement mortar, though increased PCM content filled large pores, the number of nanopores was not sufficient to maintain the desired mechanical strength. The heat storage capability of the mortar was also found to be dependent on average pore size and their distribution. It has been found that higher the number of nanopores, lower is the heat storage capability of PCM-mortar composite. The total porosity versus PCM (by weight) as can be seen from Fig. 20 indicate that lime mortar has lesser pores when compared to cement mortar. From Fig. 21, it could be understood that as the PCM content increases, the time taken to reach maximum temperature increases.

A series of experiments have been conducted by Lecompte et al. [56] to determine the thermal and mechanical properties so that the feasibility of inclusion of PCM can be determined. The results of experimentation indicate that PCM inclusion in the form of micro capsules do not contribute to the compressive and bending strengths as they behave like voids in the mortar or concrete. With 29.3% of volume fraction of PCM, a compressive strength of 8 MPa was achieved, which was deemed acceptable for building applications. The encapsulation considered here was melamine-formaldehyde. It has also been concluded that increased PCM content decreased thermal diffusivity and increased thermal inertia. It was suggested that the thermal conductivity and thermal penetration depth with increased PCM content can be increased with thermal conductivity enhancers like copper, nickel, stainless steel and carbon fiber in appropriate forms.

Cunha et al. [57] have tried combining micro encapsulated PCMs into gypsum and aerial lime based mortars. The PCM considered was paraffin in the core of the capsule. The capsule is made up of melamine-formaldehyde. The capsule is formed through poly condensation process. The results of experiments concluded that gypsum mortar is superior to lime mortar in terms of thermal energy storage because of relatively high micro porosity while lime mortar is superior in mechanical properties due to corresponding low micro porosity. The lime mortar reduced energy needs by 11% while gypsum mortar reduced it by 21%. The reason for this is good contact of ambient air with gypsum mortar because of its high porosity as stated in this research article. It has also been found that water absorption coefficients for both mortars increased when compared to mortar without PCM.

In the study, involving micro encapsulated PCM in mortars, carried out by Jayalath et al. [58], increase of PCM volume fraction has resulted in increased heat with corresponding reduction in the compressive strength of mortar. The increased PCM volume fraction as substitution for sand helped in hydration kinetics. However,

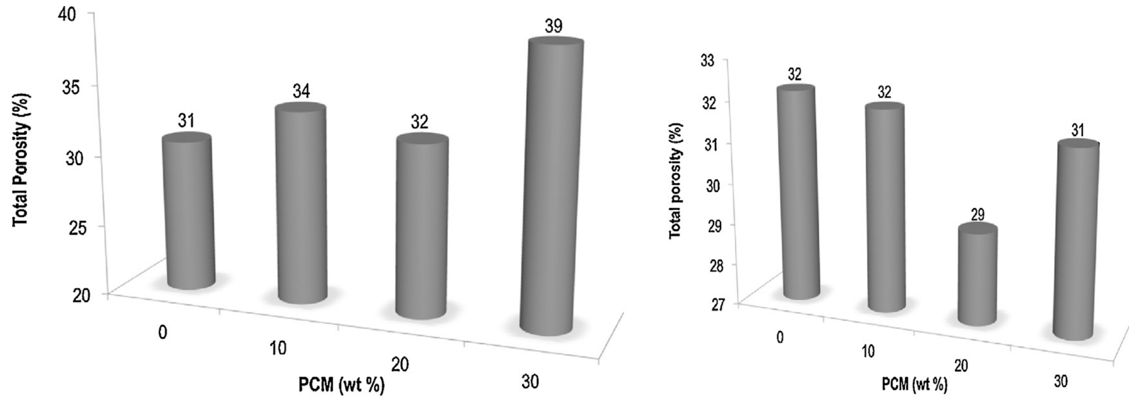

Fig. 20. Porosity versus PCM (wt%) for lime (left) and cement (right) mortars [55].

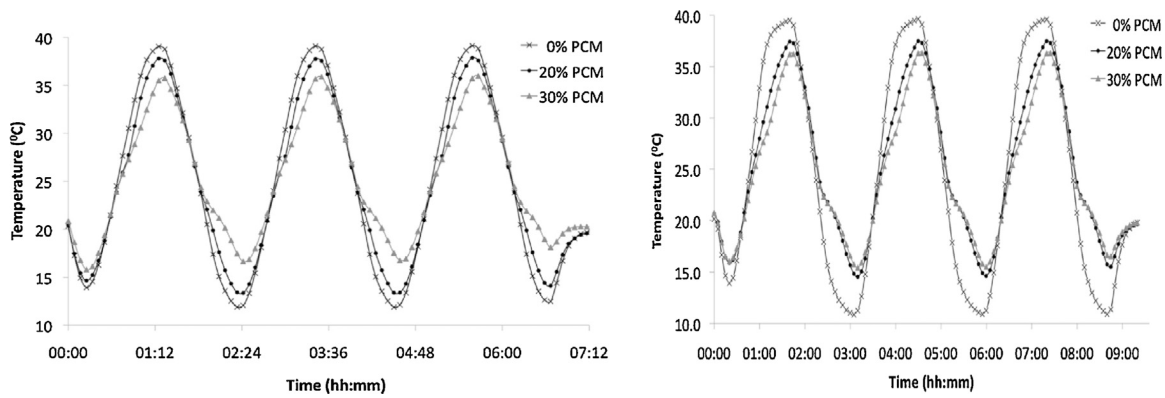

Fig. 21. Temperature versus time in test cell for lime (left) and cement (right) mortars [55].

the density of PCM being less than sand, has resulted in compromised mechanical strength of mortar. As a result, a tradeoff between thermal and mechanical properties yielded 20% PCM volume fraction as optimum for practical applications. Moreover, it has also been found that mixing process did not damage the encapsulation (polymethyl methacrylate). The result of enhanced thermal inertia due to PCM was accompanied with low thermal conductivity and diffusivity and low mechanical strength. Paraffin based micro encapsulated phase change materials (poly urea shell by interfacial polymerization) possess low thermal conductivity which is not desirable as it decreases the rate of heat transfer in the matrix.

Hence, as a remedy to the above mentioned problem, graphite flakes have been included in micro encapsulated paraffin PCM i.e., on the polymer shell and in the core of the capsule by Cui et al. [59]. Then the PCM has been incorporated into cement mortar to evaluate its effectiveness in decreasing energy consumption by operating the active heating and cooling equipment during off peak period through differential tariff system. It was observed that the compressive and the flexural strengths decreased with inclusion of graphite based paraffin micro encapsulated PCM in cement mortar but the reduction does not prevent its application in construction as it had enough strength during post addition phase too.

Moreover, it has also been found that heat of hydration decreases with inclusion of PCM thereby reducing the mechanical strength. It has been found that graphite based paraffin PCM is fully compatible with cement mortar and the thermal conductivity of cement mortar decreased with PCM inclusion and this reduction was found to be highest when the PCM was undergoing phase change. Thermal performance was evaluated for this PCM-mortar combination as presented in Fig. 22. The figures in the inset represent steady temperature variation.

A comparative study of three different plastering cement mortars has been reported by Kheradmand et al. [60]. The first mortar contained zero percentage of PCM, the second contained single micro encapsulated PCM and third contained two different PCMs with distinct melting temperatures and same mass fraction of 9.7%. The microstructure of mortars has been observed through Scanning Electron Microscope (SEM) which revealed homogenous distribution of PCM in the cement matrix. Moreover, no fractures were found at the interface of PCM and cement hydration products.

The results of DSC suggested that the thermal behavior of mortars remained consistent and accurate for two thermal heating/cooling cycles. It has been found through DSC that the shape of thermograms and peak temperatures change for changing heating and cooling rates but the specific enthalpy remained unchanged with changing heating/cooling rates. It has been observed that thermograms did not change for lower heating/cooling rate, making it evident that numerical simulations agree with experiments for lower rates of heating and cooling. Finally, it has been found that DSC tests agreed with expected thermal behavior of hybrid mortars.

Kim et al. [61] have reported that hexadecane (organic PCM) when impregnated into exfoliated graphite nanoplatelets, acts like a supportive material and also prevents leakage of PCM due to capillary and surface tension forces and also improves thermal conductivity of hexadecane. The phase transition temperature after impregnation was found to be in the range of 16–25 °C and latent heat of fusion was 96.4 J/g. The amount of hexadecane impregnated accounts for about 48.8% of the composite. The graphite nanoplatelets helped in mechanical stability and decrease the time of heat storage and retrieval.

The properties of the modified PCM mitigated energy consumption and decreased temperature fluctuations as found during the

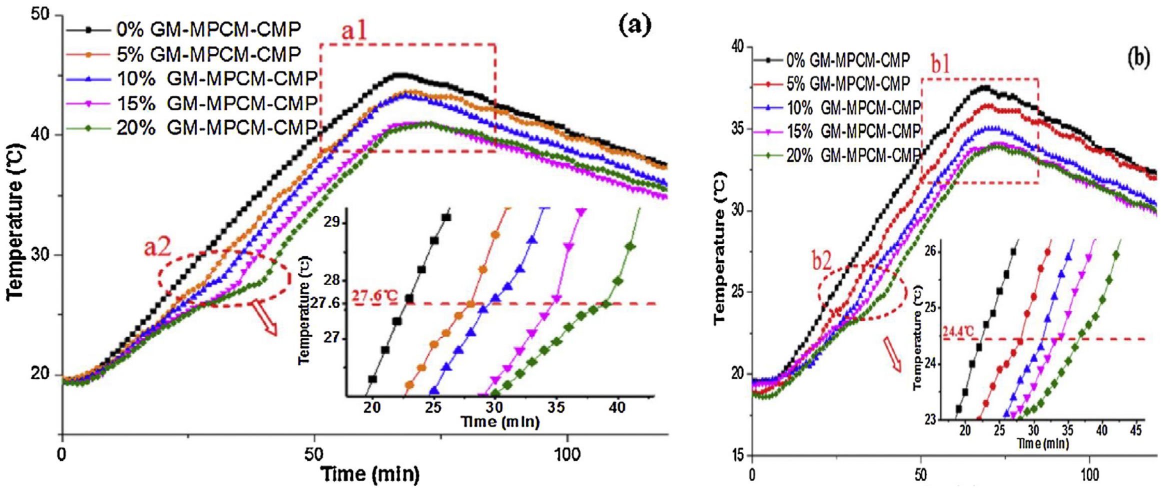

Fig. 22. Temperature variation with time over cement-graphite flakes-PCM panel (left) and in the center of test cell(right) [59].

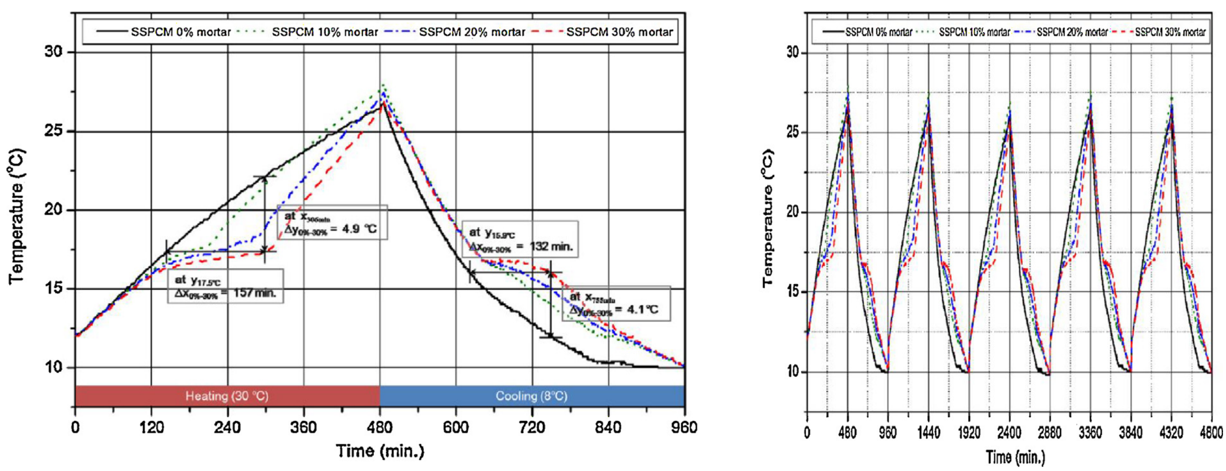

Fig. 23. Temperature variation with time for hexadecane with graphite nanoplatelets included in mortar [61].

experiments. Moreover, computational analysis was done by incorporating this PCM into mortar which indicated improved thermal inertia of cement composite mortars. Fig. 23 represents temperature variation with time for different proportions of PCM. The 5 thermal cycles indicate no thermal decomposition with time for the PCM-mortar combination considered.

The thermal conductivity of a cementitious composite containing micro encapsulated PCM has been measured using guarded hot plate apparatus. It has also been found that as the PCM volume fraction increases, the thermal conductivity decreases. It has also been found that thermal conductivity of PCM composite remains unaffected with temperature [62].

A review on different theoretical and experimental methods for improving thermal conductivity of PCM has been reported by Liu et al. [63]. The theoretical methods ranged from effective medium method to molecular simulations while experiments were conducted with enhancers ranging from carbon additives to metal nanoparticles. The effective medium has been an extensively researched and also established theoretical method.

This method has been validated through various experimental studies. The necessity for thermal conductivity improvement for PCM arises out of the fact that PCM possesses very low thermal conductivity (0.02–0.06 W/m K). This results in lower rates of charging and discharging of PCM. Sometimes, it is possible that thermal cycles may not be completed. This defeats the very basic purpose behind PCM inclusion in mortar.

So, it is necessary to enhance thermal conductivity of PCM for efficient thermal cycles. Among various carbon additives investigated for thermal conductivity enhancement of PCM, carbon fibers with highest aspect ratio had highest thermal conductivity. However, it was reported that the very process of preparing PCM composite with fibers.

Sá et al. [64] have conducted experiments to understand the benefit of using PCM in mortar for thermal comfort. A 25% mass fraction of PCM has been found suitable with a phase transition temperature between 23 and 25 °C with phase change enthalpy of 25 kJ/kg. The PCM based mortar test cell has been compared with test cell made with mortar without PCM addition as a part of experimental investigation. The test cell was subjected to realistic temperature variations simulating two thermal cycles (summer and spring in Portugal).

The optimum percentage of PCM has been worked out experimentally through many trial combinations. Then finite element based numerical simulation has been conducted to validate the numerical solution so that further parametric analyses involving changes in PCM mass fraction could be done.

A study conducted by Kim et al. [65] has reported that octadecane was impregnated in exfoliated graphite nanoplatelets to form a shape stabilized phase change material. When this PCM was incorporated in mortar, it resulted in improved heat storage properties and thermal conductivity of PCM. 55.9% of the PCM composite constitutes octadecane. It has been found through the experimen-

tal results that temperature fluctuations decreased along with the temperature disturbance propagation into the indoor space.

Paraffin included in expanded perlite has been considered as a material used for thermal energy storage in a study carried out by Sun et al. [66]. Before addition of paraffin into expanded perlite, graphite (5% by weight) was added as an additive to paraffin for enhancement in thermal conductivity of paraffin. Expanded perlite acts as supportive material imparting mechanical strength. Paraffin/expanded perlite was prepared by direct mixing method. The average percentage of paraffin in expanded perlite reached 65%. Only physical interaction was found between paraffin and expanded perlite.

The compressive and flexural strengths decreased with increasing paraffin-expanded perlite in cement mortar. 20% weight of paraffin-expanded perlite has been found as optimum quantity by weight in mortar based on the minimum strength requirements. After 100 thermal cycles only, the thermal energy storage curves started deviating slightly indicating the thermal stability of the mix proposed during the study.

Mechanical properties of different mortars incorporated with different PCM contents were investigated by Cunha et al. [67]. The PCM contents considered were 0, 20, 40 and 60% (by weight) as replacement of sand. The binders considered were aerial lime, hydraulic lime, gypsum and cement. It has been found that water demand got increased with incremental PCM quantity to achieve the desired levels of workability. Also the fineness of the PCM being used has affected the amount of water needed as the surface area keeps changing. It was generally observed that the compressive and flexural strengths of mortar decreased with increasing PCM content. This is attributed to the fact that the higher PCM had demanded the higher water requirement, thus reducing the structural strength of mortar with higher porosity. To mitigate shrinkage, a few fibre admixtures have also been used with advantage and the shrinkage cracks got reduced.

Cunha et al. [68] have tried different combinations of binders like Aerial lime, gypsum, hydraulic lime and cement as binders; PCM micro encapsulated with melamine formaldehyde with 24 °C as the phase transition temperature. Various binders incorporated with PCM were compared for their thermal and mechanical behavior. The compressive and flexural strengths have decreased with PCM addition, primarily due to high water proportion in binder. It has been also found that cracks were absent in all the mortars considered confirming acceptable physical compatibility.

Moreover, it has been reported that damage to micro capsules during mixing is absent. Thermal behavior of gypsum has been found to be superior among other mortars while aerial lime thermal behavior has been found to be inferior. This has been attributed to micro porosity in the reported research. The cost analysis indicated that HVAC requirement would be almost nil in summer, autumn and spring leading to mitigation in energy consumption cost.

In the above section, various thermal storage properties in particular have been discussed. A summary of all these works is being presented in Tables 5 and 6. Table 5 summarizes the interpretations from literature about different supporting materials. Table 6 summarizes the thermal and mechanical properties of various PCM-mortar combinations so that the reader could have an idea about the ranges of values for different properties.

4. Performance assessment of PCM-based mortars

4.1. Numerical evaluation

Numerical Simulation using commercial software or code is useful in terms of reducing the number of experimental trials to arrive at an accurate solution to the problem in hand. A few attempts have been made in simulating the structural and functional behavior of PCM based mortars. Summary of such attempts made is being presented below for quick reference.

When macro encapsulated PCM is included in building walls or other enclosures, it results in controlled indoor temperature, reduces temperature fluctuations and can efficiently utilize the solar energy to minimize the energy consumption. The poor thermal conductivity of PCM helps in controlling the transmission of temperature excitation into the interior of buildings.

A numerical study was conducted by Silva et al. [69] in ANSYS FLUENT to solve the governing equations using SIMPLE algorithm. This study tried to calibrate the numerical model with experiments. The differences between experiments and simulations were found to be within 3 °C. Although, majority of the conditions are simulated, the interface between the brick and the PCM capsule was not represented in the numerical study in an appropriate manner. As depicted in Fig. 24, the temperature profiles observed during the experimental study as well as numerical investigation, were found to be almost similar, thus making this study useful for further use.

When composite PCM was mixed with mortar, the indoor temperature fluctuations came down and the temperature range for thermal comfort also has got increased. Three different PCMs constituted the composite PCM in a study conducted by Kheradmand et al. [70]. This study involved experimental investigation for thermal behavior of composite PCM-mortar coated with extruded polystyrene board test cell and other test cell coated with ordinary mortar. It also involved numerical simulation based comparison of both the test cells for validation. One-fourth geometry was simulated in this study by taking advantage of symmetry. Through Fig. 25, the geometry of model along with mesh for numerical solution is presented. The comparison between numerical, experimental and climatic temperature profiles is presented in Fig. 26 for ready reference. Effective heat capacity method for phase change was employed. Finite volume based discretization with appropriate boundary conditions was employed during the numerical study. The error reported between experiments and simulation was within 0.1 °C. Temperature-time (TT) index was higher for composite PCM-mortar in comparison to unmodified mortar or single PCM based mortar.

When finite element method based computational model using COMSOL MultiPhysics software is used to simulate the changes in temperature in a pavement subjected to realistic temperature profiles with PCM incorporated in it, the changes were well simulated with experimental method named GLCC (Guarded Longitudinal Comparative Calorimetry), as reported by Sharifi et al. [71].

It has also been pointed out that PCM selection should be based on the temperature difference between day and night for the location considered. The case study just mentioned suggests that finite element based numerical investigation using COMSOL MultiPhysics could be considered for acquiring information related to temperature changes in a composite mortar (PCM based admixture) considering mortar as porous media and PCM to be present in the pores.

Kong et al. [72] have carried out a study in which capric acid has been used as PCM on the exterior walls and roof and a combination of capric acid and 1-dodecanol as PCM in the interior of walls and roof. The combination of capric acid and 1-dodecanol has outperformed the capric acid alone being used as PCM. Analytical work was also carried out during this research activity involving the mathematical model conceptualization, numerical analysis along with experimental investigations of the two cases considered.

The results were compared with the samples having no PCM in them. FEM based numerical simulation process followed during this research activity has yielded decent results when compared with experimental results. Fig. 27 presents the numerical temper-

Table 5
Different supporting materials for PCM included in mortar.

Supporting matrix or adsorbent	Inferences based on literature	Key inference proposed for the supporting matrix or adsorbent
Expanded perlite	Clay geopolymer mortar is most suitable substrate	All the supporting matrices or adsorbent serve as cheaper alternatives to encapsulation (macro and micro) based PCM inclusion into mortar
Expanded graphite	Thermal conductivity enhancer adsorbing PCM upto 90%	
Silica fume	Thermal conductivity enhancer and low strength material	
LWA (light weight aggregate)	Potential PCM carrier if combined with other supporting materials	
RHA (rice husk aggregate)	Potential PCM carrier combined with other supporting materials	

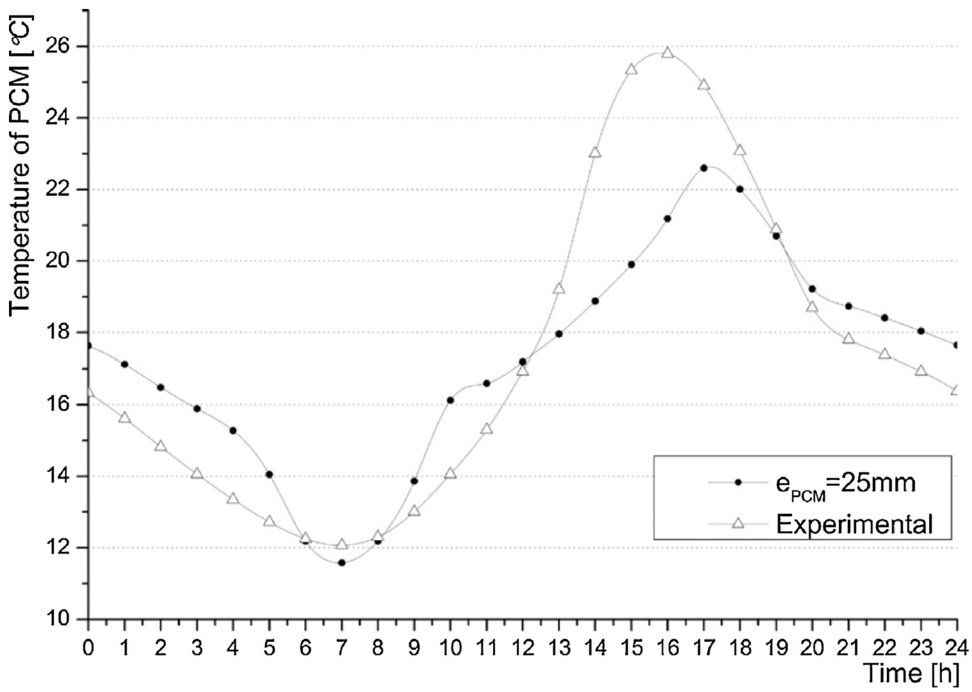

Fig. 24. Comparison of temperature variations obtained using experiments and numerical modeling [69].

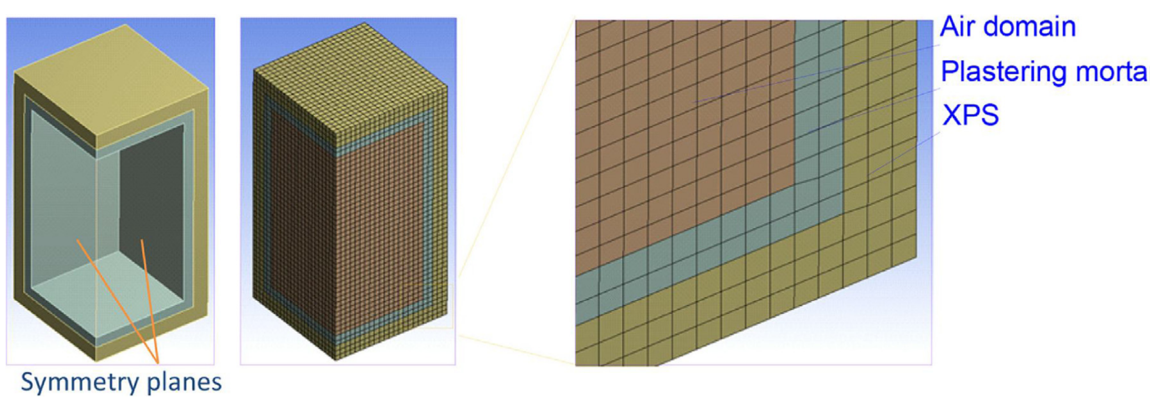

Fig. 25. 3D model along with mesh for numerical simulation-one quarter considered for simulation [70].

ature profiles obtained for both inside and outside of the building wall for both PCM included mortar and reference mortar panels.

Tittelein et al. [73] have reported that binary mixture based enthalpy model predicts the thermo physical properties of PCM included mortar in micro-encapsulated form to a greater accuracy when compared to apparent specific capacity and enthalpy method. The main motto of this study was to compare the prediction capabilities of these thermodynamic models with the experimental measurements and to arrive at best model. Finite volume method was used to assess the properties of the PCM embedded mortar.

It has been found out that apparent specific capacity method is not suitable for phase change modeling because of its poor replication of experimental results. Apparent heat capacity method predicted that the composite PCM has poor thermal storage capacity while on the contrary the experiments conducted on different samples for different temperature ranges reveal that PCM performs better. It has also been emphasized that the accuracy of experimental evaluation depends upon the sample's representation of the entire material.

4.2. Experimental evaluation

Experimental evaluation of PCM-mortar system helps in identification of critical parameters affecting the thermal and mechanical

Table 6
Thermal and mechanical properties of PCM-mortar studies.

PCM-mortar	Heat of fusion of PCM	Heat of fusion of Composite PCM or Hybrid PCM	Phase transition temperature of PCM (°C)	Phase change temperature of composite PCM/PCM-mortar(°C)	Compressive strength of PCM-mortar composite	Flexural strength of PCM-mortar composite	Reference
Paraffin/Hydrophobic expanded perlite/cement mortar	Melting-133.3 J/g Freezing-132.1 J/g	Melting-12.15 J/g Freezing-12.28 J/g	Melting-19.2 Freezing-25.5	16.3,24.6 (for melting and freezing-PCM composite)	With 43% PCM- 7.53 N/mm^2 at 28 days	–	Ramakrishnan et al. [37]
Paraffin/graphite flakes/cement mortar	Melting-248.8 J/g Freezing-249.9 J/g	Melting-135.8 J/g Freezing-137.6 J/g	Melting-28.32 Freezing-21.49	30.58,21.49 (melting and freezing-PCM eomposite)	With 30% PCM composite –14.2 MPa	With 30% PCM composite- 4.1 Mpa	Zhang et al. [38]
Paraffin/LWA/concrete	192,178,161 J/g	–	-9.5,6 and 28		Hike in compressive strength of 10%	–	Sharifi et al. [39]
[Capric acid-palmitic acid/pumice, heptadecane/pumice, dode-canol/pumice]/gypsum	CA-PA- 170 J/g, Heptadecane-228 J/g Dodecanol-205 J/g	CA-PA/pumice-56 J/g Heptadecane/pumice-72 J/g Dodecanol/pumice-67 J/g	CA-PA-24 Heptadecane-22 Dodecanol-23	CA-PA/pumice-23 Heptadecane/pumice-22 Dodecanol-23	–	–	Karaipekli et al. [40]
Microencapsulated paraffin/aerial lime, hydraulic lime, gypsum and cement	147.9 J/g	–	22.5	–	With 40% PCM at 20 °C->52% reduction	–	Cunha et al. [41]
Microencapsulated paraffin/Lime mortar	180–230 J/g	–	Freezing-19.45,Melting-26.97	26.41 (PCM-mortar)	4.1 MPa	–	Pavlik et al. [44]
Microencapsulated paraffin/cement mortar	110 J/g	–	26 °C	–	–	–	Joulin et al. [46]
Microencapsulated paraffin/cement mortar	160J/g,164.4 J/g	–	24,32	–	–	–	Thiele et al. [47]
Paraffin/expanded graphite/cement mortar	209.3 J/g	183.02 J/g	28.8	28.55 (PCM- composite)	5.1 MPa	2.01 Mpa	Li et al. [50]
Microencapsulated paraffin/cement mortar	99 J/g	–	26	–	–	–	Tittelein et al. [51]
Bio based fatty acid/concrete	Capric acid-152 J/g Lauric acid–178 J/g Myristic acid-186–205 J/g Palmitic acid-185–203 J/g	CA-LA–109 J/g CA-MA-155.4 J/g	32,42,49–54,61-64	CA-LA- 21.4 CA-MA- 26.0	With 2% CA-LA (for 28 days)- 3772 MPa	–	Cellat et al. [52]
Paraffin/expanded perlite/clay geopolymer mortar	135.46 J/g	96.77 J/g (55.47% PCM)	38.21	35.59 (55.47% PCM) (PCM-mortar)	8.0 MPa	–	Wang et al. [53]
Microencapsulated paraffin/aerial lime-gypsum	110 J/g(A) and 147.9 J/g(B)	–	22.5 (for both micro capsules)	–	With 10% PCM-600% increase (A) and 130% for(B)	With 10% PCM- 380% (A) and 85%(B) increased	Cunha et al. [54]

Microencapsulated paraffin/lime, cement and gypsum	135 J/g	–	23	–	Cement mortar(30% PCM) – >4 MPa	–	Lucas et al. [55]
Microencapsulated paraffin/concrete, mortar	180–195 J/g	–	28	–	8.3–60.5 MPa	1.7–6.1 MPa	Lecompte et al. [56]
Microencapsulated paraffin/aerial lime,gypsum	147.9 J/g	–	22.5	–	With 40% PCM, Gypsum- 78% decrease Lime-82% increase	With 40% PCM, Gypsum-67% decrease Lime-149% increase	Cunha et al. [57]
Micrencapsulated paraffin/cement mortar	100 J/g	–	23	–	33–69% decrease with 1–5% PCM by mass	–	Jayalath et al. [58]
Microencapsulated Paraffin/graphite flakes/cement mortar	248.8 J/g	126 J/g	28	10–33	32.9–65 MPa for 28 days	7.6–11.4 MPa	Cui et al. [59]
Microencapsulated paraffin/cement mortar	180.40,147.90,170.1 J/g	–	18,24,28	24 °C with 18.34% PCM for single PCM, 28 °C with 9.17% hybrid PCM	–	–	Kheradmand et al. [60]
Hexadecane/graphite nano platelets/cement mortar	257.7 J/g	96 J/g	18	16–25 (Melting) 17-12 (Freezing) (Both are for PCM composite)	–	–	Kim et al. [61]
Octadecane/graphite nano platelets/cement mortar	256.5 J/g	110.9 J/g	28	22–33 (Melting) 19–26 (freezing) for PCM-composite	–	–	Kim et al. [65]
Paraffin/expanded perlite/cement mortar	122.05 J/g	128.46 J/g	46–48, 5–6	19.45 (PCM composite)	9.27–23.88 MPa for 28 days	–	Sun et al. [66]
Microencapsulated paraffin/aerial and hydraulic lime, gypsum, cement	147.9 J/g	–	22.5	–	Minimum 37% decrease in strength for all binders for 20%PCM	>23% decrease for all binders except cement-decrease by 3% for 20% PCM	Cunha et al. [67]

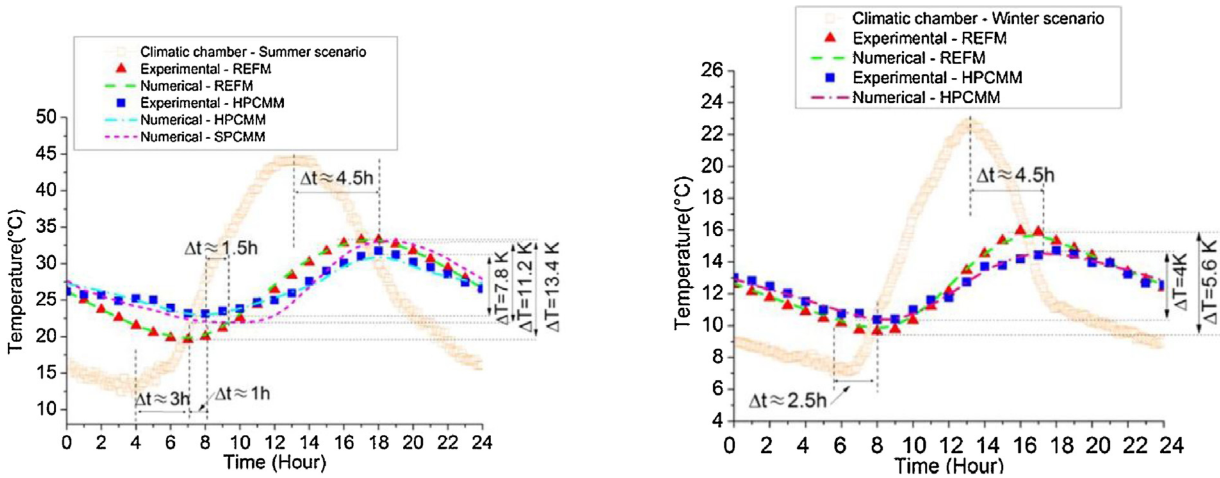

Fig. 26. Simulation results for summer and winter climatic conditions for hybrid PCM-mortar and ordinary mortar compared with experimental results [70].

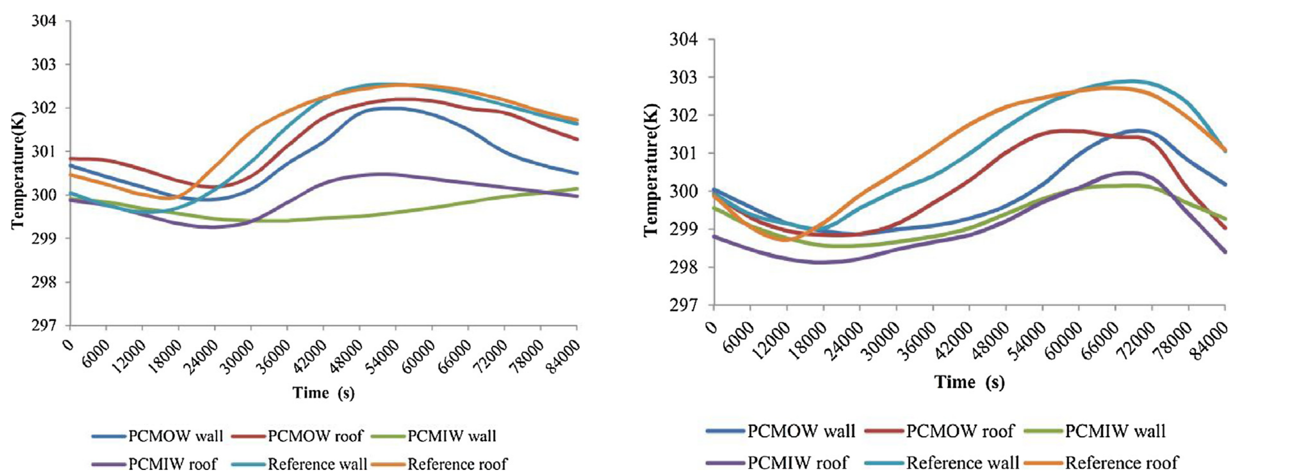

Fig. 27. Numerical simulation of temperature for roof and wall for interior and exterior with and without PCM (interior-capric acid + 1-dodecanol, exterior-capric acid) for enclosed and (open in night and closed in day)-window situation [72].

properties of system and it is mandatory for validating any new concept. But the expense associated with any experimentation is of concern. This section is devoted to the description of various experimental studies carried out for assessing whether the addition of PCM in building mortars is technically feasible or not.

A comparative study to determine the effect of incorporating PCM in clay brick walls was reported by Vicente et al. [74]. The comparison was between a wall without PCM and walls with PCM in macro encapsulated form without insulation and wall with macro PCM capsules with insulation. The PCM selected was organic paraffin and steel was encapsulating material. Steel was selected because of its high thermal conductivity. The experimental setup involved two climatic chambers and one intermediary chamber where the wall to be examined is placed.

While one climatic chamber was meant for applying the temperature profile, the other chamber was allocated for recording the effect. It was observed that the walls with PCM macro capsules mitigated the temperature fluctuations. It was also reported that the transmission of high temperature disturbance into the room with PCM took more time when compared to a wall without PCM. It was also found that there was 50–80% reduction in temperature fluctuations when compared to wall without modification. Fig. 28 represents temperature variations with time for PCM in macro capsules. The variation indicates the non-linear behavior of PCM while the zones I and II indicate the demarcation based on exposure to temperature. A and B in Fig. 28 represents two different specimens.

Pure substance model fails to represent the phase change process of micro encapsulated PCM in cement mortar. This fact was established by Franquet et al. [75] through DSC based measurements and numerical modeling. The thermogram of DSC measurements revealed the lack of symmetry in the melting and solidification phases of PCM. This was validated through finite control volume based explicit Euler integration based numerical investigations also. It was concluded that the non- conformity to the pure substance model was due to the fact that phase change was not taking place at uniform temperatures.

Eddhahak-Ouni et al. [76] have developed an experimental setup for determining thermal properties of heterogeneous composites. A bench test was conducted with the setup conceived with convection being the heat transfer mechanism involved. Both temperature and air flux rates were controlled with controlling mechanisms during this investigation. Then this setup was utilized to determine heat storage properties of PCM panels. The bench test results were compared with simple PCM compound and Energain mixture of PCM panel.

An experimental investigation of incorporating Shape Stabilised PCM (SSPCM) into cement mortar and its comparison with conventional wall in terms of thermal performance was carried out by Wang et al. [77]. SSPCM comprises paraffin wax, high density

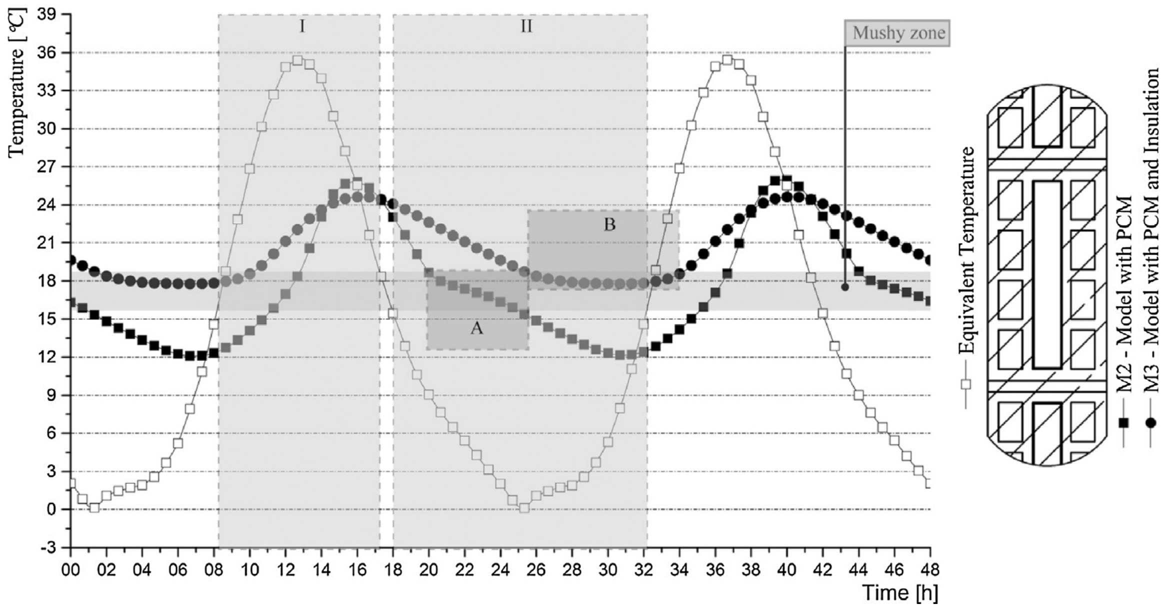

Fig. 28. Temperature variations in PCM macro capsules with time followed by schematic of arrangement of macro capsules and air cavities in hollow brick [74].

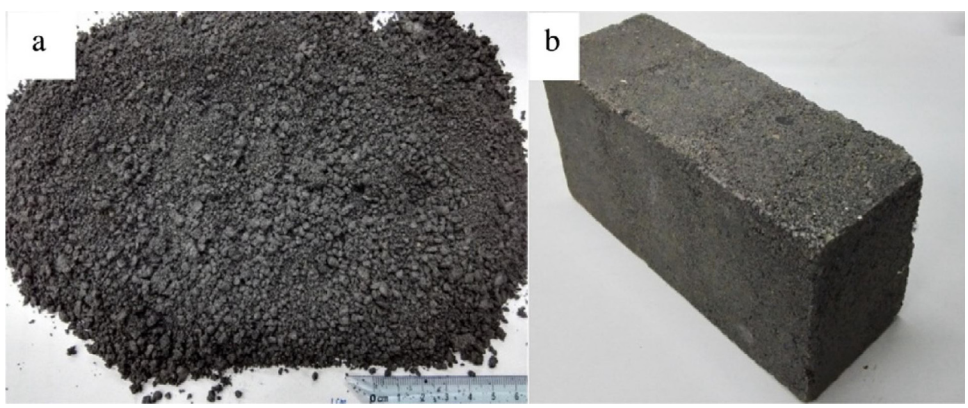

Fig. 29. a) SSPCM b) PCM based brick used for wall construction [77].

polyethylene and graphite as the supporting material. Pictorial representation of SSPCM and PCM brick are presented in Fig. 29 for reference.

It was pointed that DSC based measurements cannot give correct measurements of thermal properties for composite wall. It will give heat capacity for PCM used unlike the normal PCMs wherein the leakage is observed to be a major issue, SSPCM was found to be experiencing the evaporative leakage, which also needs attention before it being suggested for practical applications, authors opined. It has been found that the average compressive and bending strengths were sufficient to withstand light frame like structures using SSPCM. Heat capacity of PCM bricks was higher than usual wall in the range of 18–25 °C.

An experimental comparison of usage of LWA (Light weight aggregate) presoaked in PCM and LWA filled with PCM through impregnation methods subjected to compressed air drying and drying in oven of the surface were reported by Nepomuceno et al. [78]. The results reveal that as the extent of replacement of sand with LWA increases, it decreases flexural strength of the matrix. LWA filled with PCM subjected to compressed air drying has lower flexural strength than the one dried in oven. Compressive strength has improved when LWA filled with PCM is dried using compressed air. Thermal conductivity decreases when LWA of expanded clay is used as carrier of PCM. When LWA is used, it had resulted in decreased thermal storage and increased thermal resistance.

Cabeza et al. [79] have built two concrete cubicles with experimental installations, with and without PCM inclusion. The melting temperature and enthalpy were reported to be 26° and 110 kJ/kg respectively. These cubicles were compared with ordinary concrete cubicles without PCM. The results indicated that the thermal inertia of the structure increased with inclusion of PCM. In addition, the 28 day compressive strength has been reported to be 25 MPa while the 28 day split tensile strength has been reported to be 6 MPa, which were deemed to be acceptable as far as structural applications are concerned.

Shadnia et al. [80] have experimented with alkali activated geopolymer mortar incorporated with PCMs vis-à-vis the alkali activated geopolymer mortar without PCM In this study fly ash activated by sodium hydroxide was used in making the mortar. As depicted in Fig. 30, the heat capacity increases with increasing PCM content, which could be observed from the DSC results for various proportions of PCM. Moreover, the straight line for reference mortar indicates no phase change for mortar.

When expanded perlite was impregnated by fatty acid PCM (lauric acid + myristic acid) through vacuum absorption method, it resulted in 200% absorption and the mixture acted as passive temperature regulator. The loss of PCM through thermal cycling was

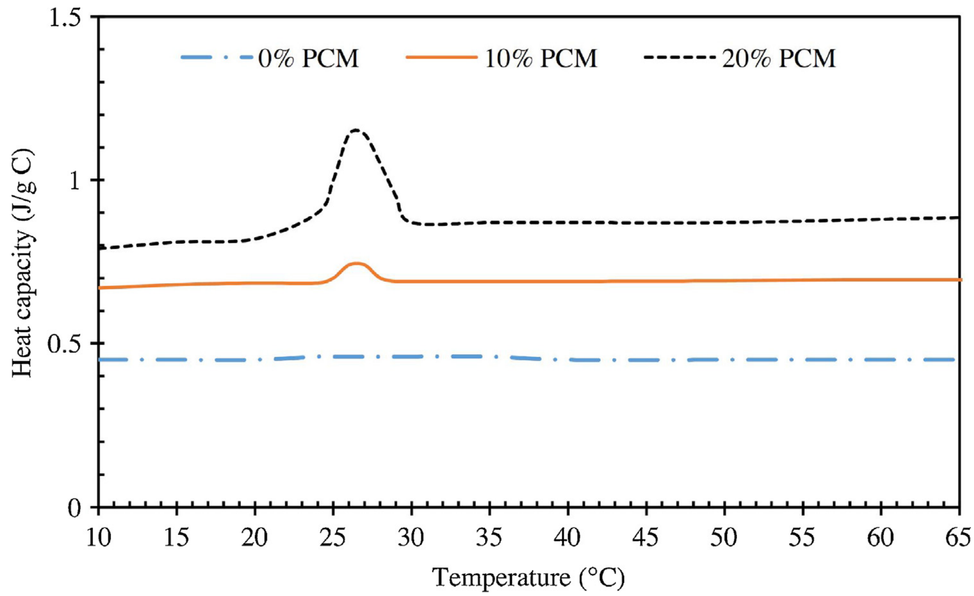

Fig. 30. Heat capacity versus temperature curves for various proportions of micro encapsulated paraffin PCM in geo polymer mortar [80].

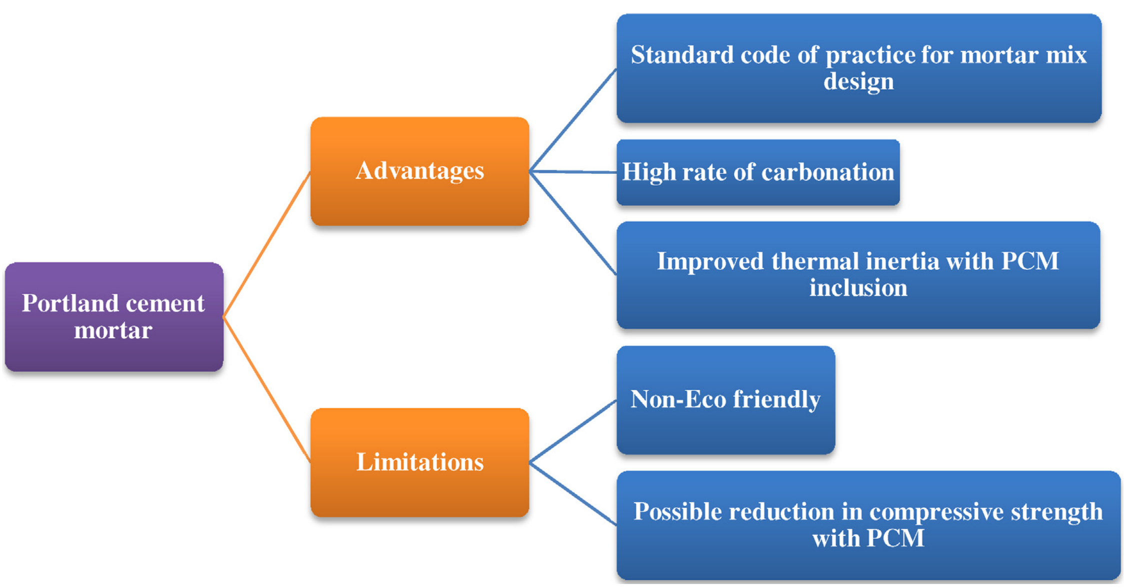

Fig. 31. Portland cement mortar-advantages and limitations.

within 3%. This was established by Miao et al. [81] in 2015 with extensive laboratory studies.

From the literature review covering portland cement, lime and alkali activated geo polymer based mortars with PCM applications, general advantages and limitations have been inferred and presented through (Fig. 31, Fig. 32 and Fig. 33) for ready reference.

4.3. Energy and sustainability

Latent heat thermal energy storage uses phase change material as storage medium. This storage medium undergoes phase change when energy is absorbed or released. In the sections described so far, the emphasis of the research reported was on determination of optimum PCM-mortar combination for improved energy efficiency of buildings. But every energy solution has its own cost. This decides its utility though the solution may be technically superior.

The reported work has very limited information regarding the cost economics after the cost escalation due to the introduction of PCMs in the building mortars. The research indicated that an improved thermal behavior of building elements through PCM incorporation reduces usage of heating and cooling equipment but comprehensive research comparing costs associated with different alternatives for different temperate zones has not yet been reported.

Shafie-khah et al. [82] have conducted experimental studies with hybrid PCM in mortar and also conducted cost analysis based on energy savings accrued with the option being tried. It was concluded that this hybrid PCM, when incorporated into walls and other structures of the building supplemented the effect of household management system in terms of cost for a specific demand response program.

L.F. Cabeza et al. [83] in their review paper have emphasized that LCA (Life cycle Assessment), LCEA (Life cycle Energy analysis) and LCCA (Life cycle cost Analysis) could be conducted for buildings to determine the environmental impact of building during different phases of life cycle of building. This paper mentions that

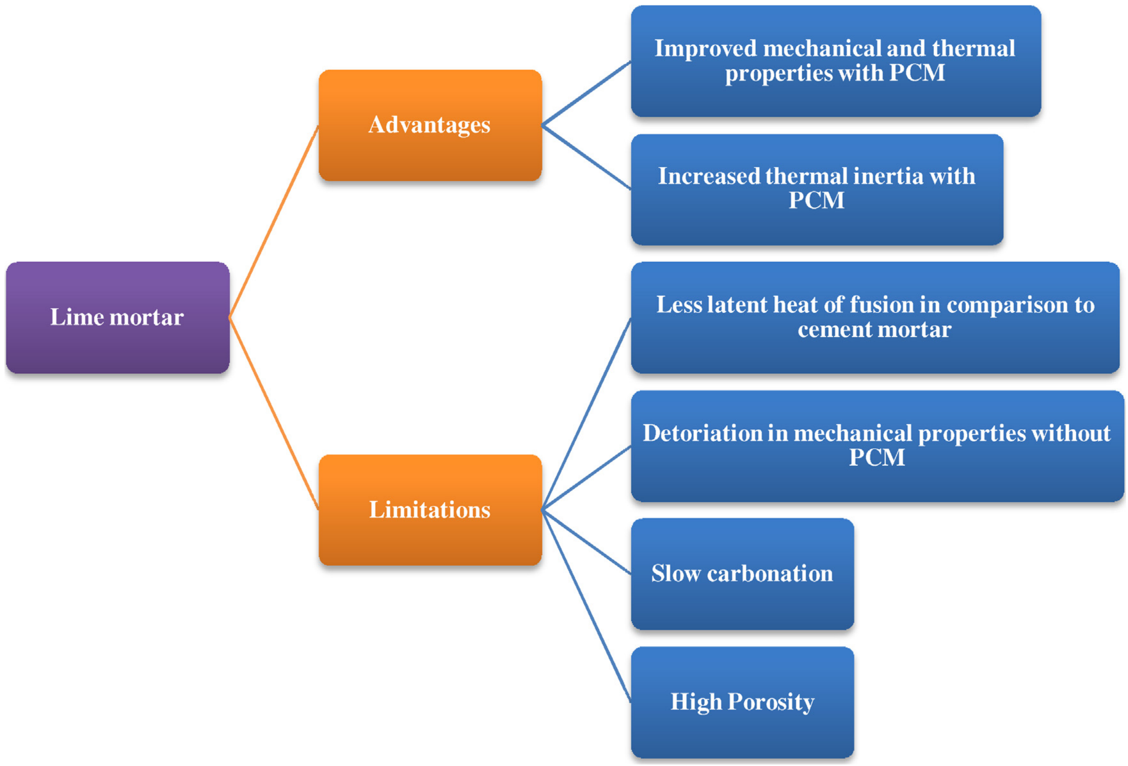

Fig. 32. Lime mortar-advantages and limitations.

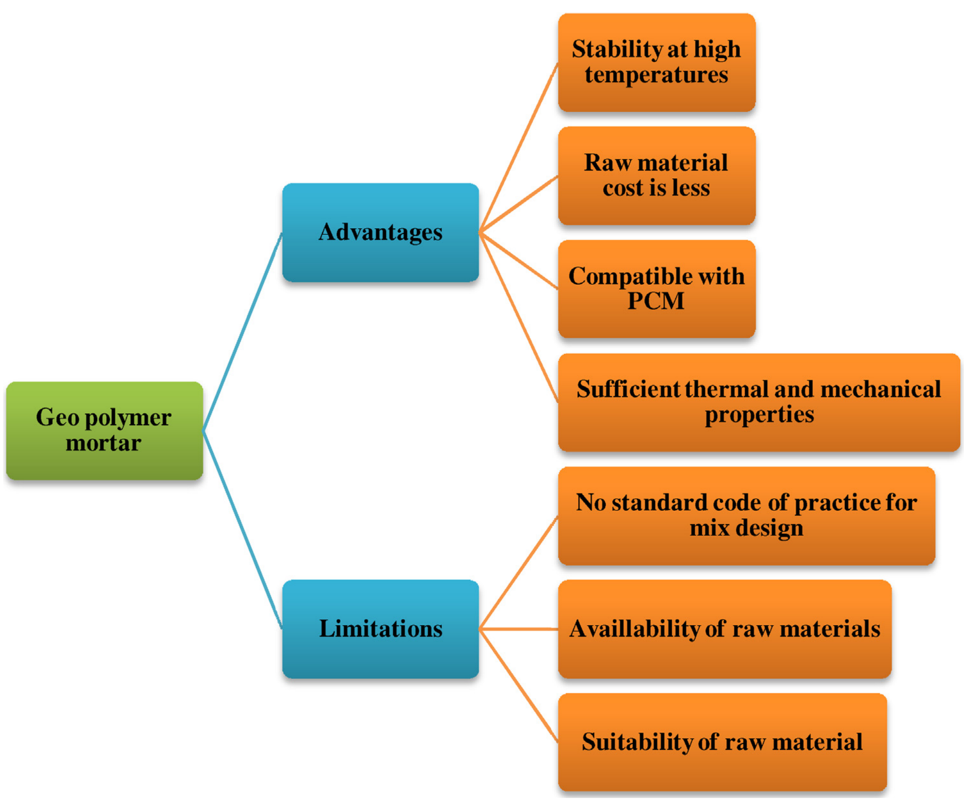

Fig. 33. Geo polymer mortar-advantages and limitations.

the buildings constructed in urban areas were only considered for environmental evaluation through LCA, LCEA and LCCA techniques.

It has been reported that buildings with PCM included in their walls are more environment friendly when compared to walls with no PCM [84–86]. Besides, there exists consistency in the LCA analyses conducted for PCM-mortar based constructions when same boundary conditions, building systems and methodologies were considered.

4.4. Scope for future research

The idea of PCM inclusion into plastering mortar to improve energy efficiency by mitigating energy demand through active systems has formed the basis for the research conducted so far. But there are certain directions in which research is not conducted which could possibly be the following:

- Comprehensive cost analysis of PCM-mortar combination has not been reported comparing all the available or proposed alternatives in the literature. This analysis should be considered for global acceptance of technology.
- Lime mortar as substrate for PCM is only being considered for rehabilitation of old buildings and monuments though the solution is promising. So, lime mortar as substrate for PCM for residential and industrial purposes can be considered
- Very little research has been reported in determining the utility of geopolymer mortar as substrate for PCM though the mortar is eco-friendly and offers economic benefits because industrial by-products and mine wastes can be used as source materials for alkaline activation. PCM considered for geopolymer mortar has been reported to be organic paraffin. Other PCM could be considered to explore possibility of its utility in buildings.
- Inorganic PCM have not been considered for incorporation into mortar of any kind may be due to their disadvantages like lack of thermal stability in the long run, phase separation, super cooling etc. But they are cheap and possess high thermal conductivity and high latent heat of fusion. A eutectic PCM like organic paraffin with inorganic PCM could be tailored to meet the desirable mechanical and thermal properties.
- A standard of code of practice for deciding mix design of PCM-mortar could be developed. Otherwise an illustrative mix design procedure for a specific case could be reported in scientific literature. This will lead to a great progress in this research area.
- Microencapsulated paraffin based PCM have been found to be considered for inclusion into mortar. Microencapsulation for organic non-paraffin could be considered as it may prevent leakage for these PCM and few PCM of this kind have been found to be renewable origin and possess high latent heat per unit mass.

5. Conclusions

Phase change material when incorporated into mortar mitigates energy consumption through active means like heating, ventilation and air conditioning equipment. PCM can be included through different methods and each one has its own merits and demerits. It should also be noted that selection of particular method depends on PCM-mortar compatibility physically and chemically. Considering the potential of PCM as passive thermal regulator, many research studies have been conducted in area of PCM inclusion in mortar. A detailed review has been conducted on these studies. Following are the interpretations based on the review conducted.

- Three different mortars can be identified from the review conducted. They are Lime mortar, cement mortar and geo polymer mortar. Lime mortar as substrate for PCM is superior to cement mortar based PCM composite in mechanical properties. But it may be noted that cement mortar based PCM composite is superior to lime mortar based PCM composite in thermal properties. Geo polymer mortar with PCM possesses good mechanical and thermal properties for usage in construction sector but it has to be noted that many experiments have not been reported using this mortar as substrate. Geo polymer mortar is suitable for cheaper constructions but its availability and suitability are deciding factors for its utility.
- The thermal and mechanical properties of PCM- mortar depend on the microstructure of PCM-mortar. As the macro porosity of the mortar increases with PCM inclusion, thermal behavior gets improved because the contact between ambient and PCM increases. Mechanical strength decreases for PCM-mortar composite with increasing macro porosity because of the absence of material to resist deformation as high porosity indicates less mass of material.
- DSC based measurement of thermal properties like melting temperature and latent heat of fusion has been found to not represent the properties of entire PCM-mortar structure in reality. This is because of the sample size (in few milligrams). Other alternatives have to be explored for reliable results in this regard like T-history method.
- Replacing sand with Light weight aggregate impregnated with mortar improves thermal properties of PCM-mortar but mechanical strength decreases. So, micro encapsulated PCM included in mortar has been found to be better option but encapsulation is expensive and microencapsulation decreases effective PCM content and thermal conductivity decreases with polymer shell as encapsulating material. Micro encapsulation in the literature reported paraffin at its core. Other PCM for micro encapsulation have not been reported.
- Non-paraffin PCM like bio based fatty acids possesses low flammability when compared with paraffin and are renewable in nature while paraffins are non-renewable in nature. But non-paraffins like bio based fatty acids are expensive when compared to organic paraffin.
- Thermal conductivity enhancement is necessary when PCM is included. Otherwise storage rate and retrieval rate from thermal buffer (PCM-mortar) decreases and incomplete thermal cycles may be possible. Improved Thermal conductivity or thermal diffusivity could be possible through impregnation of PCM into expanded graphite or dispersing graphite flakes over micro encapsulated PCM over core and shell. Otherwise enhancers like copper, nickel etc can be included into mortar.
- Numerical Simulation of PCM embedded in mortar can be conducted using Finite element method or finite volume method. Apparent heat capacity method is not suitable for PCM-mortar combination using FVM because it assumes pure substance model for PCM-mortar.

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